The Dissertation Committee for William F. McKenna Certifies that this is the approved version of the following dissertation:

Characterizing Argumentation Structure Within the Asynchronous, Online Communication of Novice Engineering Design Students

Committee:

Philip Uri Treisman, Supervisor

Leema Berland

Anthony Petrosino

Richard Crawford

Clay Spinuzzi

Characterizing Argumentation Structure Within the Asynchronous, Online Communication of Novice Engineering Design Students

by

William F. McKenna, B.A.; M.S.

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Characterizing Argumentation Structure Within the Asynchronous, Online Communication of Novice Engineering Design Students

William F. McKenna, Ph.D.

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Supervisor: Philip Uri Treisman

Practicing argumentation in secondary school classrooms benefits students both in terms of learning how to argue and learning the course material at hand. Amidst the onset and growth of engineering design courses in secondary schools, this dissertation is an exploratory case study to characterize the use of argumentation among novice student engineering designers. The setting is a high school robotics class. Specifically, a group of students from one class section teamed up with a group of students from a separate class section to design and build a single robot. The team members communicated online via a shared, editable document. That text is the primary data set for my analysis. I looked for indications of argumentation structure that emerged from the online discussion, given that, to my knowledge, the students had not been taught argumentation strategies, per se. Engineering design is relatively new to secondary school, so I thought it appropriate to develop a baseline—a case study that reveals how students communicate about their designs when left largely to their own devices. This study may inform the development argumentation scaffolds that support the students' existing strengths while ameliorating their weaknesses.

My analytical supposition was that argumentation in design will take the form of resolving differences of opinion toward the creation of a single design. Hence, I used Pragma-dialectic theory as my analytical framework. It is a broad theory, based upon resolving differences of opinion in everyday conversation. As such, Pragma-dialectic theory may also be able to encompass the idiosyncrasies of team design, such as reliance on intuition and experience, as well as the important roles that designed objects play throughout the process. Taken together, the importance of intuition, experience, and objects suggests multiple modes of communication that ought to be considered arguments within design deliberations.

Results suggest that the students worked to resolve differences of design opinions. In doing so, the students relied heavily on their designed objects to make their arguments meaningful. I classified five *object-based claims* which emerged from the students' discussions: *keystone, tinkering, visual, tactile, and counterfactual*. These form the beginnings of a theory of *object-based argumentation.*

Table of Contents

List of Tables

List of Figures and Photographs

CHAPTER 1: INTRODUCTION

The National Research Council recently published two books on precollege engineering education in the United States: *Engineering in K–12 Education* (2009) and *A Framework for K–12 Science Education* (2012). Because these publications come from the NRC, they indicate a growing national movement emphasizing the importance of *engineering* in the STEM (Science, Technology, Engineering, and Mathematics) education of precollege students. The 2009 publication emphasized *design* as the primary pedagogical organizer that should shape students' introduction to several key aspects of engineering practice and principles. In addition, the report emphasized the importance of developing six engineering habits of mind: "systems thinking, creativity, optimism, collaboration, communication, attention to ethical considerations" (NRC, 2009, p. 5). Though these habits of mind may not be teachable through any single pedagogical strategy, all of them can be learned through the practice of design. Focusing on the habit of mind *communication*, I took as my starting point for this dissertation a study I conducted in Spring 2010 at a Central Texas public school to examine how students communicate and collaborate in an introductory high school engineering design course.

In its 2012 report, the NRC emphasized more specifically the *communication* habit of mind by recommending that principles of argumentation be integrated in engineering education. The authors stated that "[i]n engineering, reasoning and argument are essential to finding the best possible solution to a problem" (p. 72) and that students in their engineering experiences should have the opportunity to "evaluate and critique competing design solutions based on jointly developed and agreed-on design criteria" (p. 69). Finally, the report authors asserted that "although the forms of argumentation are similar, the criteria employed in engineering are often quite different from those of science" (p. 72).

Such assertions are reasonable when considering how one might apply a well-known communication structure such as argumentation to the broad notion of communication within an engineering context. The criteria used by engineers are not the only significant difference between the practices of science and engineering. Engineering, especially engineering design, employs its own goals, processes, and habits of thinking. Whereas science typically begins with a sense of wonder about an observed, usually natural, phenomenon that may later be understood and characterized through scientific investigations, engineering design begins with a sense that a problem exists and that this problem can be solved, or at least ameliorated, through the creation of a new—or improvement of an existing—object or system. In fact, creating value by judiciously combining artifacts and working (scientific) principles is the heart of design thinking (Dorst, 2011), and is thus central to engineering design.

The practice of science and the practice of engineering design are of course closely related. Both are social endeavors (cf. NRC 2009, 2012), and both, therefore, involve discursive practices. In science classrooms, scientific argumentation (among students) is becoming a powerful strategy to help students develop both argumentation skills and scientific thinking skills (see Chapter 2 for literature review). The underlying assumption is that science and scientific argumentation are, in fact, inseparable. With argumentation now generally accepted as an integral component of scientific practice, it stands to reason that argumentation, in a suitable form, may also support the practice of engineering design. In addition, argumentation as a pedagogical strategy may also support the development of competent engineering design students (see chapter 2 for literature review), and, in fact, the NRC advocates for such a strategy.

But the practice of engineering design, as an artful application of science for social purposes (Waterman, 1952), and as a social endeavor, differs from the practice of science. It stands to reason that argumentation practices for engineering design might differ in important ways from those used in science. Using argumentation as a pedagogical strategy in engineering design may also differ in important ways from its use in science.

One of the central differences between engineering design and science is the role played by design thinking. For many years, researchers in pedagogy, epistemology, and the practice of design, including engineering design, have been exploring design as a social and discursive practice (by which I mean conducting purposeful observations of design teams in situ) as a way to better understand design processes and how designers think and collaborate (cf. Bucciarelli, 1994; Cross & Cross, 1995; Dorst, 2006; Harrison

& Minneman, 1995). A few scholars have utilized theories of argumentation (e.g., McDonnell, 2011; Oak, 2012; Stumpf & McDonnell, 2002; Trousse & Christianns, 1996) as a means of characterizing the discourse of design within an argumentation framework.

How best to use argumentation as a pedagogical tool in teaching design, however, remains an unanswered question. This dissertation explores this question by examining key research on design and its related discursive practices in the context of a study examining the efficacy of applying a particular theory of argumentation, Pragma-Dialectics (Van Eemeren, 1984, 2000, 2004, 2006) to analyze the discourse of high school students engaged in an engineering design challenge. I also explore the literature on scientific argumentation in classrooms for insights into the potential pedagogical advantages—and disadvantages—of explicitly teaching argumentation skills in the engineering design classroom.

If, as the NRC recommends (NRC 2009, pp. 4, 119–148), design is to be central to engineering education, we should look more deeply into the research on design and the pedagogy of design to better understand its nature, its gifts, and its idiosyncrasies—and how these can support or hinder the teaching of engineering. Further, if, as the NRC also recommends (2012, p. 72–73) argumentation is to be used to support learning communication habits of mind in engineering design, we should look into the literature that characterizes design as a discursive practice as well as into the literature that describes efforts to use argumentation as a pedagogical tool.

Making design a central feature of engineering education—at all grade and experience levels—would represent a major shift in engineering pedagogy especially in the precollegiate years. For example, Clive Dym (2005) characterizes engineering college curricula as embracing the "'engineering science' model over the last five decades, in which engineering is taught only after a solid basis in science and mathematics" (p. 103). While mathematics and science achievement and interest are clearly important, but there are other viable routes into engineering and in particular, design has special promise.

I believe that successfully integrating design into engineering curricula can benefit from examining research on design thinking, practice, and pedagogy, and on theories of argumentation as they apply to design in engineering contexts. Support for such an effort should also include field work in which researchers close examine introductory design classes to understand how students engage in engineering design practices and the role that argumentation plays in carrying out that work.

In this spirit, I conducted a study in a Spring 2010 introductory engineering design course at a high school in Central Texas. I looked for emergent characteristics of argumentation within the students' design conversations and designed the study to answer the following research questions:

1) What characteristics of argumentation emerge from students' design conversations?
2) How can pragma-dialectic theory be applied to understand the argumentative characteristics of student design discussions?
3) How do the students use their own tacit knowledge and objects to resolve design challenges, and how does their tacit knowledge relate to their argumentation practices and team design efforts?

In the fall of 2009, I was privileged to meet an exceptional teacher who had recently begun to teach robotics courses in a local school district. In observing this teacher's classes, I noticed students trying to meet certain robotics engineering design challenges and was intrigued by how they tried to reconcile their different individual views of the task at hand. I was impressed by the students' high levels of motivation and commitment to success. I observed what I sensed was the profound role that students' prior knowledge played in their design efforts. And, I was intrigued by the ways in which argumentation might be playing a role in their efforts to accomplish the class design challenge.

My first research question was motivated both by my observations of these robotics students and my readings in the literature on design and on argumentation. I wanted to explore what characteristics of argumentation could be identified in the students' design conversations because I had seen young robotics students (grades 7 through 12) arrive at surprising and impressive engineering design results without a great deal of explicit input from the instructor or other adult mentors. The teams of students had guidance, certainly, but no one was doing the work for them. My observations led me to believe that these young students' team communication strategies were, in least in some ways, effective. I anticipated observing similar communication strategies in the students observed in my study. Before introducing established argumentation practices[1] to the students, however, I thought it useful to understand how they were already communicating.

The second question—exploring applications of Pragma-Dialectic (PD) theory to understanding characteristics of the argumentation and understanding the relationship between the students' argumentation practices and their team design efforts—was motivated by the literature in scientific argumentation and team design communication. Specifically, Jonassen and Kim (2010), and Jonassen and Cho (2011) cite the work of van Eemeren (a co-originator of PD theory) as a possible tool for fostering argumentation in science classrooms and for use in deliberating ethical engineering concerns. Resnick et al. (1993), when studying students in science class, refer to van Eemeren as a resource for understanding why the students these authors observed did not engage in fallacious arguments (see van Eemeren, 1992). Though not explicitly linked in her article, Resnick's principles of *accountable talk* (Michaels et al., 2007), *are consonant with* the "rules for discussion" according to PD theory (van Eemeren & Grootendorst 1992, 2004).[2]

In addition, my readings in engineering design suggested the critical importance of resolving differences of opinion in team design (Bucciarelli, 1994; Leonardi & Bailey, 2010) and thus, Pragma-Dialectics seemed a plausible theoretical framework for exploring design argumentation. The theory of Pragma-Dialectics is founded on the premise that argumentation is a central means for resolving differences of opinion. That is, argumentation is fundamentally dialectic and incorporates the complexities of conversational interactions. My sense in reading the literature on Pragma-Dialectic theory was that its fundamental premises might be suitable to resolving differences of opinion among designers; and therefore, its further use in engineering design is worth exploring.

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[1] An *argumentation practice* includes *how* to argue, *when* to argue, and *what* to argue about.

[2] See Appendix I for an exposition on the relationship between *accountable talk* and *Pragma-dialectic theory*.

Regarding the third question, Cross (1994, 2004), Dixon and Johnson (2011), Mareis (2012), and Schon (1983, 1992), for example, note that tacit knowledge is crucial to design, including engineering design. These findings led me to assume that my students would leverage their own tacit knowledge when developing their designs. A student's tacit understanding of the world is one of the things she brings with her to class. Given the importance of tacit knowledge in design, how students use their tacit knowledge is worth investigating. Specifically, I wanted to understand the role of tacit knowledge in supporting their intrinsic or baseline argumentation strategies. From the outset, PD seemed like a good candidate for a theory to support and explicate argumentation practices in design.

As an educator, my hope is that exploring these research questions will contribute to the development of tools and strategies to help students learn the craft of design, and that these tools and strategies will lead many more students to pursue and succeed in STEM-related careers.

LIMITATIONS OF THE STUDY

This study examines novice designers' early (or first) *asynchronous* team engineering design experience. My study, however, is limited to two teams of high school students in an introductory robotics course. The challenge of generalizing from a single case study is formidable and I can make no claims of external validity. Classrooms are complex environments and what is true for one classroom is not necessarily true for others. Thus, the usual challenges to generalizability intrinsic to small sample sizes, semi-unique population attributes, and the inherently subjective nature of the analysis all relevant here.

Moreover, within this dissertation study there are a few particular limitations worth noting.

First, the local high school that provided the setting has a strong robotics culture: it has several extracurricular teams, and more students sign up than can participate. The teacher of the class I observed, Mr. John Sperry, travels with his teams across the country and hosts a number of competitions at the school. In short, robotics is cool at this school. Thus, the culture of robotics certainly impacts the students in robotics classes; however, without a comparison group, I cannot accurately determine its influence.

Second, robotics is a highly specialized form of engineering design—one that strongly emphasizes mechanical systems and commonly uses a specified inventory of parts. Thus it would be tenuous to make generalizations that go beyond mechanical systems design or that would apply to designing from scratch-built parts.

Third, the online communication available to the students in this study did not allow for the transfer of images (an unanticipated technical problem). Hence, the online communication system was limited compared to those used by practicing engineers (Leonardi & Bailey, 2010; Galloway, 2008).

Subjectivity

My analysis within this dissertation, including the creation of the coding scheme, is subjective. As a solitary analyst, inter-rater reliability, for example, did not exist, which means coding represents judgments from my own point of view. I attempted to counter my subjectivity by developing a coding scheme based on the face value of statements. Still, another analyst could disagree with at least some of my coding. Further, as the coding scheme is not directly based upon a previously developed scheme, how well it would apply to team design discussions in other setting remains unclear.

Another limitation has to do with variations in my exposure to the different teams. While observing the classrooms of periods 3 and 5, I was able to sit near the team I will later identify as Rail 1. My positioning was primarily a consequence of the arrangement of the room: my "place" in the room happened to be near Rail 1. Moreover, sitting near the team I will later identify as Stat 1 was necessarily overt and consequently felt intrusive. I could not be near enough to Stat 1 to hear them without actually sitting among them, and they didn't really go for that. As it happened, the seating arrangement caused this separation to occur in both periods 3 and 5. Therefore, my exposure to Rail 1 provided me with greater contextual knowledge of their situation, which in turn, allowed me better understanding of the force and implications of their comments in their on-line discussions. What this means is that my level of interpretation of the online discussion was not uniform across all six teams; it was not uniform across the two focus teams either. The participation of a second researcher may have mitigated any interpretive or analytical consequences of this situation.

DELIMITATIONS OF THE STUDY

I believe a strength of this dissertation study is its ecological validity. Aside from two notable interventions (described below), the study consisted of an observation of a high school robotics course engaged in a competition. The course was largely representative of what the teacher, Mr. Sperry, would have planned without my participation. Also, even though Mr. Sperry has his own teaching style, his first-year robotics classes were not markedly different in overall structure to first-year courses taught by other teachers in the school district.[3] The two interventions of note were as follows:

1) Mr. Sperry and I designed the robotics challenge competition to be different from the one proposed by FIRST Tech Challenge that year, which consisted of robots, moving at ground level, collecting small rods and depositing them in predetermined receptacles to amass points. A robot team consisted of two robots performing the same tasks (collecting rods) in a more or less collaborative manner. The challenge we designed was not what the students, or students from other classes that year, would have been doing. The primary differences were a) a team consisted of two robots performing different, yet complementary tasks; b) one robot would be moving along a horizontal pipe four feet above ground level; c) the other robot, at ground level, would not move and would have to shoot objects a distance with some level of accuracy.

2) Mr. Sperry and I had students work in an asynchronous teams with students from other sections of the class. While this approach was unusual for students in a first-year course, it was not without precedent. After-school robotics teams from rural areas of Texas have collaborated with mentors and other school teams in nearby towns, thus establishing asynchronous design environments. However, in those situations, communication was less restricted than the communication limitations that Mr. Sperry and I imposed upon our students: we did not allow emails, phone calls, texts, or planned in-person meetings between different class sections. Taken together, the changes in the design challenge and the communication requirements among the asynchronous teams impinged upon the ecological validity of this study. However, Mr. Sperry and I

[3] Many of the local robotics teachers were participants in the UTeach Engineering Program, for which I was a research assistant; therefore, I knew and had opportunities to observe each of them in their classrooms.

considered these contrived conditions carefully. We determined that they offered a reasonable facsimile of conditions encountered by practicing engineers while also fulfilling the needs of research data collection. We also believed that the students would rise to the occasion.

CHAPTER 2: LITERATURE REVIEW

PROFESSIONAL ENGINEERS STRUGGLE WITH COMMUNICATION

Communication is at the heart of team engineering work, and such communication depends not only on people skills, but also on knowledge of technical vocabulary and engineering conventions as well as the ability to converse about ill-structured problems. For example, Sageev and Romanowski (2001) conducted a survey of 193 recent American engineering graduates that helps to characterize the nature of communication problems in engineering. Overwhelmingly, the graduates in the study acknowledged the importance of communication in the workplace and described various situations in which ineffective communication had been especially problematic. The more senior engineers described by the recent graduates did not practice proper e-mail, telephone, or office etiquette, nor did the graduates perceive these engineers as able to listen carefully in order to ask the right questions. The recent graduates observed that the culture of at least some engineering workplaces placed too little emphasis on the importance of the human skills that support effective communication. These graduates also observed that too few of the engineers they encountered had been trained to share their ideas efficaciously and to anchor their ideas in the ideas of others. One respondent stated that "There are a lot of very good technical minds in the workplace, but very few that communicate effectively" (p. 689).

My interest is not in the generalities of human communication, but rather in the special communication demands that emerge when engineers engage with complex engineering problems. Even when individuals are good at grappling with differences of opinion in everyday conversations, they may have difficulty transferring that competency into engineering contexts. The literature (e.g., Boujut, 2003; Dorst, 1996; Galloway, 2008; Henderson, 1999; Leonardi and Bailey, 2008; Paretti, 2008) elaborates on these difficulties and points to an important subset of difficulties: the resolution of differences of opinion within the context of engineering *design.*

One communication challenge of particular interest arises from the nature of design work itself, and the challenge arises regardless of the designers' communication abilities. Most engineering design happens in teams, and a problem intrinsic to team design efforts is that individual engineers can view the same designed concept or object quite differently, depending on their individual backgrounds, schooling, motivation, and/or personal relationships to the object. Such influences determine an engineer's "object world" (Bucciarelli, 1988, p.161) relative to a given design. The differences among various engineers' object worlds can be significant—yet in contemporary design environments, engineers must learn to communicate between and among these worlds. While by the very nature of object worlds, there is no overarching language or means of direct translation among them (ibid.), engineers frequently use words, gestures, drawings, physical mock-ups, and various other artifacts to support their communication.

In a study of engineers working at geographically disparate sites, Leonardi and Bailey (2010) discovered that trained engineers had difficulty resolving differences of opinion despite these professionals' familiarity with the engineering concepts and their frequent use of communication technology. Specifically, a team in India performed computational analyses of automobile designs that had been developed by a team in the United States. The Indian team was highly competent and followed instructions well; however, given their lack of personal experience with the automobiles in question, they did not have the tacit understanding of automobiles that the American engineers were implicitly relying upon. Hence, the Indian engineers often did more work than was necessary and didn't compute their models as efficiently as the American engineers would have liked. The two teams interpreted the same automobile designs very differently, and thus formed different opinions on how best to proceed. The differences in this case did come from their technical understanding of engineering concepts, but from their tacit understandings of the objects under study and the uses of those objects.

The literature (Cross, 1982, 1990; Leont'ev, 1978; Minneman, 1991; National Research Council, 2000; Schon 1982, 1992; Star & Griesemer 1989) provides many examples of the ways tacit knowledge shapes understanding, thus leading to differences of interpretation and the assignment of varying meanings to apparently common ideas, designs, and objects. These situations—in which a single object (or design for an object) can be interpreted differently—provide valuable opportunities for novices to practice argumentation skills in an engineering context. Because differences of opinion can arise even in nontechnical situations—again, often situations involving tacit knowledge—resolving those differences may not always rely on purely technical discussions.

In Cross, Christiaans, and Dorst (1996) researchers analyzed video of engineering design teams and observed that the designers' interactions included multiple resolution strategies outside the realm of technical knowledge (cf. Brereton, 1996; Cross, 1996). Dorst's and others' work offers concrete evidence in support of the seemingly obvious stance that many types of statements—e.g., justifications, acknowledgments, information requests, and calling into question (Brereton, 1996)—within design discussions can play important roles in achieving resolutions. This research also suggests that the *objects* involved in the design process are important tools for negotiation (cf. Boujut, 2003; Brereton, 2000; Harrison & Minneman, 1996). As I will discuss later, the importance of objects to designers and engineers goes well beyond the objects' function as affordances for resolving arguments.

In various engineering design contexts, from designers in face-to-face environments to designers spread across the globe working on multinational design projects, communication issues can be multimodal and fed by nuance, technical issues, and interpersonal issues. Often these issues emerge from variations in perspective that originate in differences in knowledge or even in culture. As engineering companies continue to globalize, and as asynchronous design practices become more common, engineering educators face new challenges in preparing engineering students. One challenge in particular is supporting communication skills, largely in the form of written reports (e.g., Jonassen, Strobel, & Lee, 2006), during various stages of an engineering project. A second challenge is supporting primarily oral communication during the design process. Note that in asynchronous environments, oral communication may be supplanted by written communications, such as email, discussion posts, instant messages, and so on, that are less formal than reports.

In this chapter I will address these challenges by first describing existing efforts to teach communication skills in colleges of engineering. From there I will interweave knowledge from a few bodies of literature in order to characterize how people apprehend and solve design problems and how argumentation might play a role in supporting the development of design abilities. To illuminate potential connections between design and argumentation, I will start with design studies (including, but not limited to engineering design) which examine the communication that takes place between multiple designers engaged in solving a design problem. Such studies describe multiple aspects of communication, including argumentation, which I will then relate to the research on scientific argumentation to potential advantages and disadvantages for using argumentation to design work.

Next, I will return to the literature on design studies to describe the role of physical objects in design work. As I will show, objects serve multiple roles, but experts and novices treat them differently. These differences lead to important characterizations of design problem solving that include the application of intuition, tacit knowledge, explicit knowledge, and analysis. Solving design problems, then, requires knowledge that precedes articulation (i.e., intuition) and knowledge that requires articulation (i.e., analysis). The very nature of design thinking poses challenges to using argumentation—a skill that requires articulation—as a scaffold for students learning how to design (i.e., learning how to apply both intuition and analysis when solving engineering design challenges). Researchers in the cognitive sciences have studied the efficacy of using intuition or analysis when solving different kinds of problems and how the articulation of ideas can advance or impede the problem solving process. Therefore, I will incorporate research from cognitive science in order to better inform when and how argumentation might be useful in design.

Last I will propose Pragma-Dialectic theory as a potentially useful argumentation framework for analyzing engineering design discourse.

ENGINEERING COLLEGES HAVE BEGUN TEACHING COMMUNICATION SKILLS EXPLICITLY

One strategy for preparing engineers for a profession that relies heavily on communication skills is to teach—and provide opportunities to practice—these skills in school. The literature around this strategy suggests that questions remain regarding how to teach communication skills to students—even students at the K–12 level—who are studying engineering. Although there is as yet no consensus on how best to teach engineering communication skills, several programs have been emerging at the university level.

Ford and Riley (2003) reviewed various college programs, mostly cross-disciplinary efforts (e.g., engineering/arts, engineering/humanities) that were designed to improve the writing of engineering students. Results were generally promising. Lengsfeld et al. (2004) detailed a specific two-quarter course in which students studied rhetorical argumentation and used it to improve their technical engineering writing. The course has helped to increase retention rates of engineering students. Paretti (2008) provided a review of recent communication-teaching efforts in engineering, situated the teaching of communication within learning theory, and called for explicit instruction on the differences between documents in the classroom and in the workplace to show the students that they are engaged in a process for learning how to communicate effectively. In short, she recommends addressing communication directly as support for immediate learning and as preparation for work beyond the classroom. Seat, Parsons, and Poppen (2001) described a five-course minor in communication studies tailored for engineering students; results, based on student work and feedback from faculty, are promising. Yalvac et al. (2007) described a design-based research approach to integrating a single writing exercise into upper-level engineering curricula, based on best practices from *How People Learn* (Bransford, Brown, & Cocking, 1999). In the Yalvac et al. study, faculty sought to improve students' argumentation and synthesis skills, and again, results were positive. In these programs and studies, instruction in communication for college engineering students has been focused largely on writing and the use of rhetorical forms of argumentation—with a focus on producing technical documentation. Such writing occurs as a component of reflection exercises by the students. Currently, research on argumentation as a learning scaffold in design is limited, but as I will explain, worthy of further investigation.

Since the National Research Council has recommended that K–12 students learn communication as an engineering habit of mind (2009) and that argumentation be a particular focus in learning communication skills (2012), and since additional research (Galloway, 2008; McNair & Paretti, 2010) has noted that the engineering profession is trending towards asynchronous design environments, there is growing impetus for additional programs and research to enhance engineering communication skills. Given the complexity of communication in engineering, it appears crucial that prospective engineers gain practice and experience in communicative habits of mind. As I've described above, there are several existing and successful coursework programs for improving written communication skills within an engineering context. Many of these programs leverage theories of rhetorical argumentation. What remains to be studied is whether argumentation can be useful as a learning scaffold for students during team design activities. This dissertation constitutes one such exploratory study. To inform my work, I have turned to research in team design that has characterized conversational design interactions.

TWENTY YEARS OF RESEARCH ON COMMUNICATION IN TEAM DESIGN DEMONSTRATES THE COMPLEXITY OF THE PROBLEM

To finalize or prototype a design, engineers must first resolve, or at least suspend, differences of opinion around competing design ideas. Given the crucial role that tacit knowledge plays in design, including the fact that engineers must communicate across varying object worlds, reaching such resolution can be challenging. Nonetheless, teams of engineers and designers regularly do so. Ethnographic studies of engineers in practice, and studies of teams of designers using *protocol analysis*—subjects' verbalizations as data (Perkins, 1981)—provide insight into how engineers and design teams resolve their differences around a common design. I have selected studies that focused on observable phenomena, and in particular, on discourse, when investigating the design process. These studies observed primarily face-to-face communication that could be characterized as conversational. For my study, I used online discussions as my primary data set; those online discussions, however, read like talking (Davis & Brewer, 1997), and can also be described as conversational. Hence, studies that analyzed face-to-face design communication are appropriate for background information.

In 1996, Cross et al. published a collection of protocol analysis studies of a team of professional designers (with 3–5 years experience) working on a design problem. This text has become a seminal work in the characterization of design as a social activity. Three of the chapters are particularly relevant to this dissertation. Chapter 14 authors

Cross and Cross pointed out the social communicative aspects of design, including "non-committal agreements" (p. 313) and the postponement of agreement, or leaving disagreements unresolved, for the sake of expediency. These authors also noted that the designers used and relied on personal and individual knowledge and experience. The authors also described incidents of emotional persuasion. In chapter 15, Brereton et al. further characterized the designers' persuasive tactics to include appeals to "common sense, design theories, standard practices, expert practices, user preference, and demonstrations with physical hardware" (p. 339). In a later study, Brereton (2000) looked at designers' use of objects more closely and noted that they actively sought out objects to use in their thinking and communication and that the relevant meaning of the object depended heavily on the context in which it was used. In chapter 19, Harrison and Minneman examined how objects related to the designers' discourse and noted physical positioning relative to an object, gestures, and the use of objects "in conversation for the express purpose of illustrating a particular quality that could not be addressed as directly by talk or sketching" (p. 429). Together these protocol analysis studies suggest that in design situations, resolving differences of opinion can be tackled through multiple avenues, including suspension or postponement of key disagreements for the sake of expediency, a variety of persuasive tactics, and heavy reliance on the physical artifacts at hand.

A few researchers have examined design communication from the standpoint of argumentation. Trousse and Christiaans (1996) considered design a discursive activity and investigated the design process using a linguistic theory of argumentation "inspired by the topoi of Aristotle" (p. 368). *Topoi* in this context represent argumentative rules that relate to counterfactual exercises (Bucciarelli, 2002) or "if…then" proposals, that designers often perform while interacting with a drawing or physical mock-up. For example, if we rotate the air foil by 10 degrees, the windmill will rotate faster. The topos argumentation model thus defined is closely related to the design process (at least according to Bucciarelli and Schon) but may not, applied in isolation, allow sufficient room for investigating the *persuasive* (as opposed to factual and counterfactual) aspects of designerly discourse. Stumpf and McDonnell (2002) created a fairly elaborate argument construction based on *The New Rhetoric* (Perelman, 1971), writing "[a]s a tool to illuminate the design process we [Stumpf and McDonnel] are studying the interplay of reality construction and persuasive figures to analyse and model design discourse, allowing to express what steps are taken on a communicative level" (Stumpf, 2002, p. 14). Most recently Oak (2011) explored the use of theories of *symbolic interactionism* (Plummer, 2000, as cited in Oak, 2001) and *conversation analysis* (Drew, 2005, as cited in Oak, 2001) to understand design and design interactions.

There have also been more straightforward interpretations of argumentation in design studies. Brissaud (2003), in an experiment involving five professionals, defined "the argumentation (process data), [as] a collective building of knowledge about the project, used to evaluate and validate each technical choice" (p. 162). Brissaud took this approach to help determine efficient ways to store *information* about previous product solutions and *process data* about how previous designers arrived at that solution. In a study of college-level design teams, Fleming (1997) noted that the students used a *claims-evidence-warrant* structure of argument when defending their design proposals. In this study, however, it is not clear that the same argumentation structure was used when the students were *creating* their design proposals. Karacapilidis and Trousse (1997) described an online argumentation support tool to aid designers in their negotiations of design ideas. The argumentation structure was based on issues, alternatives, positions, and preferences. (The website referenced in the article is no longer available.)

Over the past 20 years, then, various structures and approaches for argumentation in team design have been explored. Such studies have used argumentation models that range from erudite (e.g., *topoi* in Trousse and Christiaans, 1996) to more common interpretations of rhetoric (e.g., Fleming, 1997). To date, however, there is by no means consensus on the nature or utility of any particular argumentation structure for modeling—or clarifying—design interactions. Any such structure would have to encompass a broad range of communication strategies including persuasion, gesture, object references, technical design language, counterfactual exercises, and supporting claims with evidence. It may well be that *design*, by its very nature, does not lend itself well to being practiced or improved through formal argumentation structures, or it may be that the appropriate argumentation structure(s) to carry out effective discourse around design has yet to be determined.

The absence of an accepted formal structure of argumentation in design could also be cultural. Argument in science, and proof in mathematics, are considered integral to those areas of study, but in my research, I have found no analogous argumentation structures for design. For instance, whereas "scientific argumentation" is its own area of study, it has no immediate kin in the world of design. In a theoretical exploration of how designers resolve differences during the design process, Bucciarelli "focus[ed] on the languages of design, not solely the languages of object worlds, but the more vulgar language of negotiation and deliberations across these domains" (2002, p. 221). In other words, designers use a mix of everyday language as well as the language of initiated professionals.

RESEARCHERS HAVE LEARNED VALUABLE LESSONS FROM STUDIES IN SCHOOL SCIENCE CLASSROOMS

Research in middle and high school science classrooms suggests that scientific investigation and scientific argumentation are mutually supportive practices. That is, students learn to argue about science while arguing to learn science (Andreessen, 2006; Jonassen & Kim, 2010). To study argumentation practices, specially designed classroom exercises provide students the opportunity to observe compelling natural phenomena for which they must formulate the best possible explanation given the information at hand (cf. Cavagnetto, 2010; Erduran, Simon, & Osborne, 2004; McNeill, Lizotte, & Krajcik, 2009). Typically, students work in teams and try to formulate a single explanation that they can all support. In such classes, students are engaging in an argumentative practice that involves making and rebutting claims and supporting their assertions with salient evidence and references to appropriate theories or laws (Jiminez-Aleixandre, Rodriguez, & Duschl, 2000; Kuhn, 2007, 2010; Osborne, 2004). In these situations, the students' thesis statements and arguments should adhere to scientific standards of reasoning (Engle & Conant, 2002; Ford & Wargo, 2007).

Research in science classrooms suggests that focusing on argumentation is a promising pedagogical strategy. In classrooms using such an approach, students learn how to participate in a social argumentation structure, and the nature of their arguments become more scientific even after a relatively short experience with argumentation strategies (Sampson, Grooms, & Walker, 2011). Glassner (2005) reported that students in 8-grade classrooms demonstrated an ability to recognize the epistemic strengths associated with the use of explanations versus the use of evidence in accomplishing different goals. Specifically, the students in Glassner's study recognized that the strategy of citing *evidence* is more effective when trying to prove a claim, whereas the strategy of *explanation* is better when trying to convey "the causal basis of a claim" (p. 108). Berland and Reiser (2008) showed that students constructed stronger scientific explanations when they were focused on the argumentation goal of persuasion. These examples are part of a growing body of research demonstrating that argumentation-based activities in science classrooms enable students to learn both argumentation skills and scientific concepts. Furthermore, in a study by Sampson and Clark (2009), when students in science classrooms worked in teams, the quality of their arguments increased both for individuals and for the collective after participating in a team.

Equally important to my work are recent research discoveries about the nature of students' ability to argue and about the challenges they face when developing argumentation skills. Students in a study on 10th-graders tended to rely more heavily on personal experience than on scientific theories, laws, or models when forming explanations of observed phenomena (Sampson, Grooms, & Walker, 2011). They struggled to differentiate between evidence and inference, and to use and evaluate evidence for the purposes of argumentation (Berland & Reiser, 2009; Kuhn, 1991; McNeill, Lizotte, & Krajcik, 2006; Sandoval & Milkwood, 2005). Students struggle both because they do not know what evidence counts as justification (Duschl, 2008; Sadler, 2004) and because they do not know what the available evidence means. Perhaps as a consequence, students in high school science classrooms tend not to rely on available evidence or appropriate reasoning when deciding whether to accept or reject an idea (Sampson, 2009). Judging whether an explanation is valid or acceptable is also made difficult as students rarely use criteria "consistent with the standards of the scientific community" (ibid., p. 453).

Students in high school and middle school science classrooms also have difficulty mastering the more social aspects of argumentation. Preferring to work towards scientific accuracy, some students will ignore the persuasive aspect of argumentation and make unintentionally ambiguous statements to their peers (Berland & Reiser, 2009). In other words, students may be inattentive to the needs of their audience as they focus on the accuracy of the message itself. In groups, high school science students tend to ignore contrary opinions (Schwartz & Glassner, 2003), or make it difficult for other students to gain the floor (Barron, 2003; Engle & Conant, 2002). Students can also tend to exhibit a confirmation bias by only attending to evidence that supports their claim and to those other students who agree with it (Sampson, Grooms, & Walker, 2011). A general tendency among students who are novices in the skills of argumentative discourse is to focus more on supporting their own arguments and less on considering the arguments of their opponents (Kuhn & Udell, 2007). Further, this tendency may be exacerbated by the cognitive demands of conducting argumentation while incorporating theoretical knowledge in the context of scientific explorations (ibid.).

ENGINEERING DESIGN MAY HAVE BOTH ADVANTAGES AND CHALLENGES FOR LEARNING ARGUMENTATION

If, then, as described above, focusing on argumentation discourse in science classrooms can increase student skills both in argumentation and in science, it is reasonable to wonder whether one would see similar results when using argumentative discourse in engineering design. Broadly speaking, there is a fundamental commonality between argumentation in both settings. During scientific inquiry, students discuss in order to formulate and agree upon the best explanation for an observed phenomenon that incorporates all the evidence at hand and aligns with scientific principles. In design activities students discuss in order to create the single best design they can build given the design constraints and resources available. Although somewhat different, both exercises can be fundamentally characterized as the resolution of differences of opinion—in science, toward a common explanation, in design, toward a common design solution.

In fact, design contexts may hold certain advantages for learning argumentation practices. Students employ stronger scientific explanations when engaged in persuasion, and persuasion is central to design deliberations. Hence, the persuasive context of design settings may naturally promote the development of argumentation skills. Yet persuasion, among other aspects of design discourse, commonly takes place among a team with motivation to cooperate towards making a final, best design. Since argumentation ability increases through participation in teams, design may again be a well-suited setting. Having to work as a team to create the best design (to win a robotics competition, for example) may also support students' willingness to not only strengthen his or her own arguments, but to attend to the arguments of others on the team. In scientific contexts students tend to rely more heavily on personal experience than on scientific theories, but in design personal experience can be a valuable asset and can even serve as persuasive evidence. This is because design is the creation of value (Dorst, 2011), and that value is interpreted by, among other things, a designer's personal experiences with the world.

At this point one could formulate several research questions regarding the efficacy of argumentation practice within a design context. But since argumentation within design—as a scaffold for design deliberations—remains relatively unexplored, I took a step back and asked a more basic question:

> **Research Question 1:** What characteristics of argumentation emerge from students' design conversations?

This is an important question to ask when observing novice students because much of what is known about how designers deliberate during a design process has been learned while observing professionals, primarily in laboratory settings. Professionals and novices treat design differently, as I will explain later. Understanding how novice design students interact of their own accord is a good first step in creating argumentative learning scaffolds that enhance their existing strengths and ameliorate their weaknesses.

Further, it's known that design discussions contain a mixture of everyday language and the language of object worlds. Given that object world language stems from academic or professional initiation into a particular field of study (e.g., solid state mechanics, fluid mechanics, chemistry, material science, management) it's reasonable to assume that novices will use little formal design language and favor explanations, descriptions, etc., based on common, everyday language. This tendency has also been seen in students in scientific argumentation exercises. Since design discussion incorporate a large range of language types, it may be useful to examine student design discussions through an argumentation framework that characterizes everyday conversations and makes space for more technical, object world language.

Pragma-dialectic (PD) theory asserts that argumentation serves the purpose of resolving differences of opinion. As I have described, resolving differences of opinion fits both scientific and design discussions, but may be more suited to design discussions where opinion based on personal experience are highly valued. I will describe PD theory in greater detail later in this chapter, but for now it's important just to recognize that PD theory attempts to characterize argumentation as it occurs in everyday communication. However, it does not rule out technical, even erudite, language. It does this by establishing that the discussants determine for themselves what counts as a valid or convincing argument. If the discussants are answerable to specific cultural standards or reasoning, uses of evidence, etc., so be it. It's up to the discussants to apply those norms to the discussion (resolution of difference of opinion) at hand. Normative language structures of science or engineering design, for example, are not inherent within PD theory.

This principle may be extremely important. Professional designers have to work across the differing languages of object worlds, and there is no over-arching, universal design language. A multidisciplinary design team comes to the table carrying different languages, different values on evidence, and potentially different standards of reasoning. If they are to leverage an argumentation structure to support their deliberations, that structure should allow for the discussants to negotiate what it means for an argument to be convincing. The same is true for novice designers. Even though they may not be contending with the boundaries of formal object worlds, they are dealing with different sets of personal experience, all of which are potentially valuable. Novices may benefit from an argumentation structure that allows for arguments based on personal experience and understanding. This brings me to

> **Research Question 2:** How can Pragma-dialectic theory be applied to understand the argumentative characteristics of student design discussions?

Within a design context, it is quite possible for designers to have to choose between two or more competing ideas (opinions) which are both well-founded and align to scientific and engineering principles. Similarly, for novices especially, it's possible to have to decide between two or more competing ideas (opinions) based on little more than personal experience or preference. In fact, as I will explain later, professional engineering designers often rely heavily on personal experience. Of course, an instructional goal here is to help students to make arguments that are rigorous and anchored in known principles (e.g. engineering, scientific). But it would be desirable to use an argumentation theory that focuses on resolving differences of opinion while allowing for a broad range of ways to argue for or against an opinion.

One more, possibly significant, advantage (and challenge) for learning argumentation in a design setting lies in the use of physical objects as affordances for making arguments and as the end goal of those arguments. Objects could provide potential reduction of cognitive demand on students as communication tools or foundations upon which to build arguments. As Cross (1982) explains, an object can convey important information without words:

> Objects are a form of knowledge about how to satisfy certain requirements, about how to perform certain tasks. And they are a form of knowledge that is available to everyone; one does not have to understand mechanics, nor metallurgy, nor the molecular structure of timber, to know that an axe offers (or 'explains') a very effective way of splitting wood… A significant branch of designerly ways of knowing, then, is the knowledge that resides in objects (Cross, 1982, p. 225).

Bucciarelli (2002) asserts that designed objects are themselves linguistic—they communicate information, even stories, in ways that are not strictly bound to language. Therefore, these objects may provide vehicles through which students can "articulate" their own tacit understanding of them. In other words, the students' own physical creations may provide useful or even necessary elements of student arguments that would otherwise be very difficult to put into words. The object itself may help make an argument convincing (e.g., by serving as a proof of concept). Although using objects to support and clarify discourse about objects may provide some advantage in communication, such use is not simple. Design is complex; there is no single agreed-upon process (Guerra et al., 2012), and the design, and the designed object, tend to evolve over time.

Design Conversations Anchor to Physical Objects

Schon (1992) describes "designing as a kind of experimentation that consists in reflective 'conversation' with the materials of a design situation. A designer sees, moves and sees again" (p. 135). "Each move is a local experiment which contributes to the global experiment of reframing the problem" (Schon, 1983, p. 94). This "conversation" with the design materials is not locked into an explicit, predictable process; it is fluid and marked by multiple decisions informed by theoretical and experiential knowledge.

As the conversation (between designer and design situation) evolves, the designer's knowledge can complexify and emerge in the relationship between designer and object. That is, the design problem and its possible solutions are continuously reframed in a logical "pattern of 'if…then' propositions that relate the cumulative sequence of prior moves to the choices now confronting the designer" (Schon, 1983, p. 99). At various development stages, the designer develops a web of possible design moves based on knowledge, imagination, and the current status or configuration of the design. At some point, the web of possibilities becomes too complex to hold in the mind of the designer, and he or she must then move to a decision that reifies one or more of the proposed possibilities. This decision commonly results in a drawing or a physical mock-up. Now the drawn or mocked-up object embodies the memories and knowledge of the designer up to that point. From there the counterfactual exercise (Bucciarelli, 2002; Hilpinen, 1993) continues with new "if…then" proposals. Hence, the conversation between designer and object proceeds as an iteration of proposals for change and the physical manifestations of decisions.

An important consideration, especially when studying the design processes of novice students, is that these design conversations develop regardless of the designer's level of theoretical knowledge. The conversations can become very complex and meaningful to the designer; they are steeped in—and originate from—the designer's understanding of the situation: the past, present, and future of the design. As noted earlier, the designer's understanding of a design, or his or her *object world* (Bucciarelli, 1988), can encompass, in the case of professional engineers, varying responsibilities and interests regarding the outcome of the design. Managing engineers, machinists, and chemists, for example, can all see the same design differently, based on their individual responsibilities and their previous training from particular fields of study—which shape their individual object worlds. Object worlds also emerge through "different kinds of heuristics, metaphor, norms and knowledge as codified, tacit and know-how" (Bucciarelli, 2002, p. 224). Novices then can interact with designed objects differently, and operate from different object worlds. For them the differences depend less on the results of formal study and more on personal experience, cultural influences, upbringing, some prior schooling, etc.

Boundaries between object worlds can be fuzzy or opaque, and designing engineers have to negotiate across these boundaries to achieve a shared vision of the design in question. This task is made more difficult because there is no "over-arching object world proper language" (Bucciarelli, 2002, p. 228) with which to achieve that shared vision. And relying on better articulation by each engineer of his or her object world may not suffice if the object worlds are grounded in different academic disciplines with their own jargon, definitions, and language strategies. Still, such negotiations are often successful. One method of negotiation common to engineers relies on physical artifacts such as sketches, drawings, models, and so on (Bailey, Leonardi, & Barley, 2010; Henderson, 1999; Subrahmanian et al., 2003).

In fact, Ferguson (1994) asserts that drawings are the primary link between designers and manufacturers. Drawings, models, and other artifacts serve as "common ground" and the "records of reconciliation" between designers and manufacturers (Subrahmanian, 2003, p. 193). In this dissertation, the students in my study are both designers and manufacturers. The artifacts are like "notes to self" as the students change roles along their own design project trajectory.

Within a design context, objects serve in multiple roles. They are a record of past decisions in an ongoing conversation (Schon, 1983). They are themselves linguistic, in the sense that they are an embodiment of meaning—mathematical, theoretical, aesthetic—from which designers can develop deeper understanding (Bucciarelli, 2002). Once embodied, a design, and the engineers' previous and current understandings of it, can once again be experimented upon, counterfactually or otherwise, or the embodied design may instead be used as the basis for future negotiations.

Objects, then, are the common ground between different designers' different object worlds, and as such, objects serve as a record of prior resolutions. Hence, the designed object will play an important role in whatever communication (including argumentation) structure the designers employ. Design, and in particular, the creation of a prototype designed object, offers an opportunity to recognize students' existing knowledge and experience as valuable assets to use in solving challenging problems.

Design literature suggests that both tacit knowledge and physical objects play critical roles in design activities including design conversations. Because this appears to be true for experts and novices alike, I can assume that the students in this dissertation study will use tacit knowledge and physical objects to some degree in their design activities. What I am looking for is how this behavior is revealed by their design discussions.

> **Research Question 3:** How do the students use their own tacit knowledge and objects to resolve design challenges, and how does their tacit knowledge relate to their argumentation practices and team design efforts?

I am also looking to see if argumentation in some form may be a useful scaffold to support this dual use of that which is inherently implicit and hard to articulate (tacit knowledge) to that which is overtly explicit and reified (the object). Communicating tacit knowledge is known to be difficult. At the same time, describing robotics assemblies is also difficult, especially without an established lexicon. I wonder how the students manage it!

EXPERTS AND NOVICES BEHAVE DIFFERENTLY IN DESIGN CONTEXTS

This dissertation examines whether argumentation can be an effective learning scaffold for novice engineering design students. As such, it's worth looking at how the behaviors and competencies of experts and of novices differ in design contexts. Understanding these differences can help contextualize the nature of the students' use of argumentation in this study.

From protocol studies of junior and senior industrial design students, Christiaans and Dorst (1992) (as cited in Cross, 2004) noted that "some [junior] students became stuck on information gathering, rather than progressing to solution generation" (p. 430). On the other hand, senior students were able to work with less information and process it more quickly to build up a mental image of the problem. Atman et al. (1999) found that "subjects who spent a large proportion of their time defining the problem did not produce quality designs" (p. 142). These results suggest that experts tend to move toward the creating of solutions quickly (Cross, 2004) and do so based on a useful mental image of the problem.

Higher sophistication of mental visualizations of design problems is a mark of expertise. "[N]ot only do better initial mental problem representations have a direct impact on development expertise, but they also promote successful problem solving via increased proactivity" (Bjorklund, 2013, p. 153). In fact both novices and experts use mental representations—in the form of analogy—spontaneously throughout the design process. Experts tend to use more schema-driven analogies (i.e., more abstract analogies, or schemas, derived from experience with similar problem types), while novices use more case-driven analogies (i.e., more concrete prior examples that can be directly mapped onto the current problem) (Ball, Omerod, & Morley, 2004).

Analogies in design are also described as *within domain* (case-driven) and *between domain* (schema-driven). Within-domain analogies are used when comparing two types of the same thing (e.g. two coffee cups, two robotic armatures). Between-domain analogies are used to compare different things with similar traits (e.g. robotic armature to a human arm) (Dixon & Johnson, 2011; Ozkan & Dogan, 2013). With findings similar to those of Ball (2004), Dixon (2011) found that while both experts and novices used between-domain and within-domain analogies, experts used more of both types of analogy and seemed to prefer between-domain analogies; in contrast, novices used more within-domain analogies. According to Ball (2004) and Cross (2004) analogy-use results sort this way between experts and novices because moving between domains requires a level of abstraction that experts can more easily achieve, in part because they have witnessed more examples of more varied types. Research on analogy in design, then, suggests a pathway to expertise that is based on development of a library of experiences with physical objects that can be drawn upon to create mental representations that help solve new design problems.

It is interesting to note that in design, experts tend not to completely abandon novice problem-solving strategies. Design experts typically have the ability to apply any one of a number of schema-based analogies that can lead them to solve new problems in an almost routine manner (Ball, 2001). However, when experts are faced with non-routine aspects of a problem, and no schema-driven solution is available, they turn to more case-driven analogies to find a design solution. This practice can be seen in Dixon and Johnson (2011) when experts used more within-domain (case-driven) analogies than the authors expected because, the authors noted, none of the expert designers were "fully conversant about motorcycles" (p. 9). In other words, the motorcycle produced non-routine aspects of the design for which the experts did not possess appropriate between-domain (schema-driven) analogies. The authors concluded that the important difference between experts was not the type of analogy they used, but rather in the experts' strategic and appropriate use of multiple types of analogies.

Novices have been observed to use trial-and-error techniques to iteratively generate, implement, and evaluate design modifications and to spend time engaging in tasks that help them understand a design's function or assembly (Ahmed et al., 2003). On the other hand, experts in that study seemed to be aware of the reasons behind a particular component, were aware of relevant issues and could prioritize among them, and often referred to past designs through memory, drawings, reports, and colleagues (ibid.).

In a sense, the trial-and-error process still emerges even among experienced professionals. The term *satisficing* denotes "problem solving and decision making that sets an aspiration level, searches until an alternative is found that is satisfactory by the aspiration level criterion, and selects that alternative" (Simon, 1972, p. 168). Since then the term *satisficing* has been adapted by design researchers and has been identified in the practices of professional engineers (Atman, 1999; Ball, 1997, 1998; Cross, 2004; Guindon, 1990).

Another important characteristic that distinguishes the behaviors of experts and novices in design is the ability to utilize and balance multiple modes of cognition, including intuitive and analytical thinking. This distinction is important to this dissertation's investigation of whether particular discourse structures enable or hinder the learning of novice engineers, so I will further explore this notion by expanding my literature base beyond the pedagogy and practice of design and engineering and into cognitive psychology—specifically, intuitive decision-making, implicit learning, and tacit knowledge.

THE USE OF INTUITION AND ANALYSIS IN PROBLEM SOLVING AND DESIGN

The literature on design I have referenced thus far is rooted in the work of Donald Schon, Herbert Simon, and Michael Polanyi. There is another strand of research with similar roots, including the work of Arthur Reber, that has been influential in the fields of psychology, social psychology, and (to some extent) design, that focuses on how people make decisions. Findings from this literature provide insights into how people, designers and otherwise, reason and make decisions when faced with various kinds of information and problems. Such insights provide context that will be helpful when considering how to use reasoning and problem-solving scaffolds such as argumentation to support student learning in engineering design courses.

Hammond (1996) proposed a continuum of human cognitive activity "that is identified by intuitive cognition at one pole and analytical cognition at the other (p. 147, as cited in Hogarth, 2002, p. 7). A key distinction in Hammond's model is that one process (analysis) can be made explicit, whereas the other process (intuition) cannot. Neither process, however, is intrinsically more valid or accurate than the other. In fact, an empirical study of professional civil engineers showed that when faced with various types of problems, intuitive and analytical thinking strategies were both successful—and which strategy was used depended on the information at hand (Hammond et al., 1987).

It turns out that intuitive (or tacit) processing works best with more complex inputs, and analytical (or deliberate) processing works best with less complex inputs (Dijksterhuis, 2004; Hammond et al., 1987; Hogarth, 2002; Schooler & Melcher, 1995). The determination of what, exactly, constitutes *more complex* and *less complex* can depend in part upon the individual (Hammond et al., 1987). Nonetheless, research on this dual-process model of cognition asserts that individuals solve problems via a range of cognitive processes, from intuitive to analytic. "The tacit system is always involved in making judgments and choices but can be subject to control by the deliberate system" (Hogarth, 2002, p. 4).

A quick note on terminology: *Tacit*, *intuitive*, and even *unconscious* (cf. Dijksterhuis, 2004) are defined as existing at one end of a cognitive continuum, while *explicit*, *deliberate*, *analytic*, and *conscious* (ibid.) are defined as existing at the other end. Hogarth (2002) uses *tacit* and *deliberate* to operationalize *intuition* and *analysis*. Dijksterhuis states, "Conscious thought refers to the cognitive and/or affective task-relevant processes one is consciously aware of while attending to a task" (2004, p. 586). Unconscious thought refers to task-relevant processes outside conscious awareness (ibid.). The conceptualization of *tacit knowledge* is credited to Polanyi (1962) and has been oft regarded as that knowledge which is not explicit; however, as Virtanen (2010) points out, even Polanyi did not conceive of a dichotomous system—of *tacit* and *explicit*. Rather, Polanyi (1958) operationalized the idea of knowledge through the concepts of *focal awareness* and *subsidiary awareness* (as cited in Virtanen, 2010).

All these terms are not interchangeable, however, and researchers must be careful about their use. Fortunately, differentiating these terms' particular nuances is not critical to this dissertation. At least some of the influence on terminology choice comes from the disciplines in which the researcher-author was trained. It would appear, in fact, that the various authors are attempting to describe the same object, but from the perspectives of different object worlds.

Important to this dissertation is the fact that in the literatures I examined, the use of *intuition* versus *analysis* when solving problems relates to levels of expertise. Building on a long history of dual-process research, Pretz (2008) extended the work into the domain of problem solving. In two studies of college students (N=184, N=119, respectively) solving authentic problems related to college life, Pretz found that neither intuition nor analysis was more effective than the other, but that the efficacy of one over the other depended on the level of experience of the student. For younger students (novices) intuitive processes produced better results, while for older students (experienced) analytical processes worked better. The study did not produce conclusive results, but it did extend, rather than contradict, previous theory in this area (cf. Berry & Broadbent, 1988; Schooler & Melcher, 1995).

In a study of novice and expert design engineers, Dixon and Johnson (2011) found that both groups used *heuristics*—a rule of thumb based on experience that codifies intuitive thinking--and mathematical formulas when designing their solutions. The difference in their levels of use was a matter of balance. For novices, the breakdown for all the propositional statements recorded in the protocol analysis was 88% heuristics and 12% formulas; for experts, the breakdown was 55% heuristics, 45% formulas. (As noted above, the seemingly high rate of heuristic statements for the experts in this study may have been due to their lack of familiarity with motorcycles, a critical element of the design problem in the study.) Even though design quality was not accounted for, the study reinforces the finding that more experienced problem solvers tend to invoke more analytical thinking, while novices tend to invoke more intuitive thinking.

There seems to be a relationship between the complexity of the problem, the levels of experience, and the cognitive problem-solving strategies used. Intuitive strategies tend to be more suitable when problems present themselves via an array of complex or incomplete information. Analytical strategies tend to be more suitable when the information is more simple and complete. When faced with complex information, an expert may work to solve the problem intuitively, but also has the ability to extract simple information from the complex for the purposes of analysis. Without this ability, novices tend to prefer intuitive strategies. In design, then, a key characteristic of expertise may be the ability to strategically balance the use of intuitive and analytical thinking strategies as appropriate to the problem.

This taxonomy of cognitive processes can also be seen in the use of analogies. When people "make judgments by recognition or similarity, [t]hese [(tacit)] processes operate quickly and automatically but are driven by only parts of the actual stimuli; [those judgments] are heavily dependent on features that are common to both objects" (Hogarth, 2002, p. 18). The dual-process (intuition/analysis) theory of cognition was developed through research in cognitive psychology, but it clearly applies to design in that it relies on the comparison of objects. As described above, designers use analogies frequently, but experts tend to use more schema-driven (between-domain) analogies than case-driven (within-domain) analogies (Ball, Omerod, & Morley, 2004; Dixon & Johnson, 2011). Certainly, a distinguishing feature of experts in design is that they have been "exposed to a large number of examples and solutions that occur in their domain. But a key competency of an expert is the ability mentally to stand back from the specific of accumulated examples, and form more abstract conceptualizations” of them (Cross, 2004, p. 432). Using schema-driven analogies involves abstracting similar key features from a range of concrete examples. Abstraction is an analytical process, and it appears that experts develop both intuitive thinking skills and analytical thinking skills simultaneously and perhaps sympathetically.

Myriad studies have compared the task performance of subjects using more intuitive or more analytical problem-solving approaches (see Evans 2009, 2010; Plessner, 2008 for review). When subjects in the process of solving problems are instructed to provide reasons for their moves or solutions, performance on intuitive tasks goes down, while performance on analytical tasks goes up (Hammond et al., 1987; Macchi & Bagassi, 2012; McMacking & Slovic, 2000). In other words, verbal explanation appeared to support analytical processing, but it diminished intuitive processing. On tasks related to the judgment of art and music, Dijkstra (2013) found interaction between verbalization and quality of judgment. Among the subjects, judgments were made either before or after deliberation, which included writing down 3 to 6 reasons for their judgments. Novice judgments and expert judgments were unaffected by whether deliberation had occurred before the judgments were made. Subjects with an intermediate level of experience, though, made poorer judgments after deliberation. The acts of verbalization or deliberation (with written expression) affect cognitive strategies, but that effect is mediated by the relative expertise of the individual.

A look at the work of Polanyi (1966, 1969) may help explain these implications of verbalization in cognitive processing. I am turning to Polanyi because his work is a common root feeding into both (1) cognitive psychologists developing the dual-process model (Evans, 2009; Reber, 1989) and (2) design researchers working to understand designerly thinking and the pathways to expertise (Cross, Naughton, & Walker, 1981). Starting with the now-famous premise, “There are things we know but cannot tell” (Polanyi, 1962, p. 601), Polanyi developed a theory of knowledge based on awareness. “[T]he content of *focal awareness* was conscious and thus subject to verbal description. However…focal (or ‘explicit’) knowledge was always based on tacit knowing in *subsidiary awareness*” (Virtanen, 2010, p. 755, original emphasis). In developing this theory, Polanyi did not establish a dichotomy between two forms of knowledge—e.g., tacit versus explicit—rather, he articulated a process in which knowledge originates on the tacit level and then percolates to the conscious level where it becomes available for articulation. In other words, what is left unsaid is not fundamentally unsayable; there is no ontological barrier between tacit and explicit (Duguid, 2005, p. 110). However, attempting to articulate knowledge that is tacit is not always worthwhile (Duguid, 2005).

As Virtanen (2010) argues, traditional epistemology is primarily concerned with the truthfulness and justification of beliefs. Polanyi's theories are more concerned with the mental processes by which those beliefs are formed. In this sense, tacit knowledge precedes explicit knowledge, or, perhaps more accurately, tacit knowledge informs explicit knowledge. This theory of knowledge development has been supported empirically in studies of implicit learning in which subjects are able to express an understanding of a contrived grammatical system or effectively control a video game system prior to being able to explain the rules of those systems (see Reber, 1989 for review). In such experiments, *understanding* preceded articulation. To be clear, it's not that tacit knowledge absolutely defies articulation. Such knowledge can be articulated, but in articulating tacit knowledge, it becomes the object of focal awareness, and thus stops being tacit. Furthermore, as research indicates (cf. Hogarth, 2002), the attempt to articulate tacit knowledge (defined as intuitive reasons, unconscious thought) diminishes—by slowing—its virtue as a problem solving cognitive process. Ultimately, tacit knowledge is subordinate to justification and determinations of truthfulness; however, the development of tacit knowledge precedes such judgments.

Designers certainly use their tacit awareness of the world to inform their designs. But it isn't an awareness that trumps analytical rigor. Rather, the modes of thinking work in concert. In design contexts, both modes are pertinent and valuable, and educators ought to be aware of both in order to nurture both.[4]

Summary

Below I outline the main ideas from my review of the literature on design research and dual-process cognition. Each statement is not unequivocally true, and the

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[4] A useful ontological comparison can be found in the work of David Hammer and Andres Elby (2003) in physics education which is based on the p-prims of Andrea diSessa.

known caveats will be addressed in this chapter. I believe, however, that the brevity provides clarity.

1) Design researchers consider *tacit knowledge* important in design
2) Tacit knowledge processing, otherwise referred to as *intuition* or *implicit learning,* is especially valuable when performing tasks or solving problems for which the inputs are large in number and/or complex.
3) *Analytical thinking*, otherwise known as *deliberate thinking* or *explicit knowledge*, is especially valuable when performing tasks or solving problems for which the inputs are few and/or simple.
4) Novices and experts (especially designers) tend to use both kinds of thinking—*tacit* and *explicit*, *intuitive* and *analytical*.
    a. Novices are more successful with intuitive approaches and less successful with analytical approaches.
    b. Experts are able to balance the two approaches, using either one as the situation demands.
5) Articulating one's thinking tends to diminish intuitive processes and tends to support analytical processes.
    a. As argumentation depends upon articulation, argumentation lends itself more readily to analytical processes.
6) The two problem-solving approaches reveal themselves in expert and novice uses of analogy.
    a. Experts use more schema-driven (*between domain*) analogies, which involve a level of abstraction across many examples.
    b. Novices use more case-driven (*within domain)* analogies, which rely on a direct mapping from example to solution.
7) Novice designers tend to use trial-and-error processes, and these processes continue into expertise in the form of *satisficing*—a process that exists between theoretical design methodologies and guesswork.

Based on the literature, I anticipated that because the design challenge in my study was complex with varied and incomplete inputs, the students would be relying heavily on intuition and tacit knowledge. Further, due to their lack of experience, their use of analogy would be limited and they might not be able to hold sophisticated mental images of their design ideas. All these surmisals led me to suspect that the students would have difficulty communicating their design ideas, particularly online, where more articulation is required than during face-to-face conversation.

Descriptions on the use of intuition, analysis, analogy, and satisficing among designers provide clues as to how the students in my study are going to operate. The clues are not prescriptions, however, so it is important to ask the relatively open Research Question 3: How do novice students use tacit knowledge and physical objects in their design activities? How designers think is by no means thoroughly understood, and these students may provide new insights. Addressing the question will certainly be guided by clues from the literature.

After learning about the realities of team design efforts, I grew more concerned that argumentation, in any form, might not be present in the students discourse at all. In order to investigate, and hopefully alleviate, this concern, Leema Berland and I conducted a pilot analysis on a portion of one team's online discussion posts (Berland & McKenna, 2010). The discussion posts set was incomplete because we conducted the pilot analysis during the Spring 2010, semester when the robotics challenge was not yet complete.

PILOT STUDY FOR THIS DISSERTATION PROVIDES SOME EARLY FINDINGS RELEVANT TO ARGUMENT ABOUT DESIGN

In this pilot analysis, Dr. Berland and I examined the online discourse of one of the six teams of the high school engineering design students whose learning processes are the focus of this dissertation (Berland & McKenna, 2010).[5] We looked for elements of argumentation using an analysis method similar to that used by Erduran et al. (2004), with a framework originally derived from the work of Toulmin (1964)—that is, claims supported by evidence connected through warrants—or explanations as to why the evidence supports the claim (see also NRC, 2012). Our results showed that the students

[5] For reference, the one team studied was Rail 1, who went on to be one of the two focus groups of this dissertation.

exhibited elements of argumentation according to a framework common to research in scientific argumentation, and we were able to classify six different types of justification (or support for their claims) in their discourse.[6] In short, the students in the pilot study made claims and supported them with some sort of evidence relevant to their design. Argumentation was present within their discourse.

Even though these results were promising, further reading of the online discussions of Rail 1 and that of the other five teams in the dissertation study led me to doubt that this particular argumentation framework described the essence of their discussions. Further, I began to doubt that scaffolding with any sort of argumentation structure would benefit these students' design work meaningfully. For example, from the pilot analysis, we concluded that instructing the students to provide specific reasons for assigning tasks within their teams would be a point of useful support. However, after reading the online discussions of all six teams, I began to suspect that if a student assigned a task without providing a specific reason, it was because the student did not actually know a specific reason. Guiding the students, then, toward an argumentation structure of claims supported with evidence didn't seem to fit the situation of novice designers relying on tacit or intuitive knowledge.

Argumentation as a communications scaffold remained compelling, however, so I continued along this line of investigation. I found that Pragma-dialectic (PD) theory (Van Eemeren & Grootendorst, 1984, 1996, 2004) offered a perspective on argumentative discourse distinct from the discourse models I had found in the scientific argumentation literature. I'll now list a few key features of pragma-dialectics (along with a few reasons I chose it), and later further expand upon these features. First, PD theory provided a framework that encompassed the entire conversation, of which argumentation is but one stage. PD regards "arguments as statements made to increase the acceptability of a standpoint" (Mercier, 2012, p. 306). This model seemed appropriate, because in a complex design problem with a lengthy design process, students must engage in argumentation on issues as they arise. Particular points for argument vary across different teams and design challenges. Second, PD theory is focused on the resolution of differences of opinion, which, as I described above, is an intrinsic component of design

[6] I discuss the results more thoroughly in Chapter 4.

discussions. Third, PD does not prescribe a particular linguistic form for what counts as a convincing argument (i.e., it does not require that an argument consist of claims based on evidence). Rather, the discussants determine for themselves what makes an argument convincing. This criterion is therefore rather loose or permeable, but I did not want to presuppose what form convincing arguments would take. Rather, I wanted to uncover what the students themselves believed to be a convincing argument. In short, PD theory provided for me a useful framework through which to examine the data. I will now describe key aspects of the theory in more detail.

PRAGMA-DIALECTIC THEORY IS USEFUL FOR ANALYZING THE RESOLUTION OF DIFFERENCES OF OPINION

Pragma-dialectics views argumentation as an explicit means for resolving differences of opinion (Van Eemeren & Grootendorst, 1984, 1996, 2004). PD offers a model of argumentation in which a discussion takes place between two discussants: the *protagonist* and the *antagonist*. One party, the protagonist, asserts some "standpoint" (Van Eemeren, 2004, p. 2), and if the other party, the antagonist, does not accept the standpoint, a discussion begins regarding whether and how the standpoint could be accepted or rejected. The protagonist puts forth arguments to support the adoption of the standpoint, while the antagonist critiques those arguments to undermine the given standpoint. If the protagonist withdraws the standpoint in light of the critiques, the standpoint is rejected. If the antagonist withdraws the critiques, the standpoint is accepted. At this point, the discussants may proceed to a new discussion on a different standpoint or a modification of the previous standpoint. This protagonist/antagonist relationship was established as a model to support analysis, but those roles are not necessarily assigned to particular individuals. Rather, the protagonist and antagonist are roles defined by the making of arguments for (protagonist) or against (antagonist) the standpoint at hand. Multiple participants can contribute to either role. Different members of the discussion may assume these roles as the discussion proceeds. With a change or shift in standpoint, discussants may assume different roles.

Because design is inherently an exercise in resolving competing criteria (Dorst, 2006), and because designers in a team must resolve their own differences of opinion

(Bucciarelli, 1994, 2002), pragma-dialectics may be well suited to help clarify and accelerate that process. Also, communication between designers is conversational and includes a wide array of statement types, from technical (Henderson, 1999), to affective and interpersonal (Brereton, 1996; Cross, 1996), to physical demonstrations in which words serve a supporting role (Fleming, 1997; Harrison & Minneman, 1996). PD can address those conversations because it is based on speech acts and recognizes the complexity of verbal interactions.

Pragma-Dialectics Has a Dual Purpose as Analytical Tool and Normative Guide

> The pragma-dialectical model of a critical discussion is a theoretically motivated system for resolution-oriented discourse. Although the model is an abstraction, rather than merely serving as a Utopian ideal, it should provide people who wish to resolve their differences by means of argumentative discourse with vital guidance for their conduct. The model must be constructed in such a way that it can serve not only as a paradigm for systematic reflection upon one's active oral and written participation in argumentative discourse, but also, and even more so, as a point of reference in analyzing and evaluating argumentative discourse. In addition, it can be a standard for guiding the methodical improvement of argumentative practice (Van Eemeren, 2006, pp. 6–7).

Pragma-dialectic theory, then, is both an analytical tool and a normative guide. It provides a method for post hoc assessment of argumentation as well as guidance for discussants engaged in the resolution of differences of opinion. Both the analytical and the normative aspects of PD are complex and are largely sorted by delineation between those statements that serve the resolution process directly and those that influence the conversation but do not directly contribute to the resolution process. Some statements belong to the "critical discussion"—a defined subset of the statements in a conversation—while others belong to the conversation but not the "critical discussion." PD marks this delineation by classifying types of speech acts (for a table, see van Eemeren & Grootendorst, 2004, p. 67–68) and axiomatically asserting which ones belong to the critical discussion and which do not.

> In pragma-dialectics, the central question in the analytical component is how argumentative discourse can be reconstructed in such a way that all those, and only those, aspects are highlighted that are relevant to resolving a difference of opinion on the merits. The resulting analysis can therefore be characterized as resolution-oriented (Van Eemeren, 2006, p. 3).

The PD analysis is done by identifying the illocution of various statements within a conversation. Then, by processes of elimination, rearrangement, and interpretation (or clarification), the analyst reconstructs the conversation (taken as a resolution of differences of opinion) using only those statements that contribute directly to the critical discussion. In this way, the resolution process can be judged against a theoretical ideal model (also described by PD) for resolving differences of opinion.

Note that in this study, I am not trying to judge the students' arguments against a theoretical ideal. Rather, I am trying to identify what traces of argumentation exist within the students' conversations as viewed through the lens of PD. This exercise is about characterizing the students' speech acts, not assessing their efficacy. I will consider their conversations to be attempts to resolve differences of opinion. I will consider the illocution of their statements, but I will not use the PD speech act rubric (see van Eemeren & Grootendorst, 2004, p. 67–68) to segregate their statements either within or without the critical discussion. I will use the four stages of a critical discussion as defined in PD as an analytical guide to describe the flow of the students' design resolution processes.

PD is Based on Speech Acts

Pragma-dialectics assumes that all utterances within a critical discussion are speech acts (Searle, 1976, 1980; Grice, 1975)—that all utterances have both explicit and implicit meanings. Van Eemeren and Grootendorst (1984) make this assumption in order to describe a theory of argumentation that can encompass a broad range of verbal interactions that covers a range of discourse contexts—from everyday conversations to highly formalized talks.

> Unlike both formal and informal logical approaches to argumentation, the focus in pragma-dialectics is on the way in which language is used, or should be used, in argumentative practice to achieve communicational and interactional goals (Van Eemeren & Grootendorst, 2004, p. 53).

In developing their theory, Van Eemeren and Grootendorst realized that in resolving differences of opinion, discussants use many types of speech acts. Some of these acts contribute directly to the evaluation of standpoints, while others contribute indirectly by guiding the overall course of the conversation. As such, all utterances are considered to play important roles in the conversation (Van Eemeren, 2006). Because the pragma-dialectics theory is based on speech acts, PD helps to convey the complexities of argumentation as a component of conversational interactions.

Pragma-Dialectics Defines Four Stages to a Critical Discussion

The four stages are established by discursive markers of important events within a discussion. Each stage is marked and created by utterances from one or more discussants. According to PD theory, each of the stages *will occur*, but the clarity and usefulness of each stage is not predetermined. Again, PD characterizes argumentation as one part of a critical discussion, and the entire discussion must be properly nurtured for argumentation to successfully resolve a difference of opinion. The entire discussion is marked by four stages: *Confrontation*, *Opening*, *Argumentation*, and *Concluding*.

Confrontation Stage

The confrontation stage is marked by some representation of awareness on the part of the discussants that a difference of opinion exists.

> In the confrontation stage of a critical discussion, it becomes clear that there is a standpoint that is not accepted because it runs up against doubt or contradiction, thereby establishing a difference of opinion (Van Eemeren, 2004, p. 60).

This characterization is relatively straightforward if the standpoints and lack of acceptance of those standpoints are made explicit. However, an important and more nuanced feature of the PD confrontation stage is the allowance for implicit differences of opinion. For a difference of opinion to remain implicit, "it is either assumed in the argumentative exchange of views that a difference of opinion exists or the possibility of a difference of opinion is anticipated" (ibid.). In practice, the confrontation stage may be marked by a single standpoint whose acceptance is in dispute or by a constellation of interrelated standpoints, any one or all of which may be subject to disagreement and will require argumentation to resolve. Also, the antagonist may assert counter-standpoints in lieu of, or in addition to, critiques of the existing standpoints. Such complexity makes argumentation difficult, and in practice, not all standpoints within a constellation can be argued simultaneously with satisfactory results. Hence, identifying and choosing which standpoints to argue and which to postpone becomes an important aspect in resolving differences of opinion.

Opening Stage

The opening stage is marked by the establishment of an initial premise, for or against the standpoint, which the discussants will argue. Typically, discussants are already formulating arguments to use to support their initial premises. Hence, discussants generally attempt to form premises with "the status enjoying the widest agreement" (Perelman, 1969, p. 179). "This explains why actors often attempt to enhance the status of personal feelings and impressions to that of widely shared value judgments and the status of subjective values to that of facts" (Van Eemeren, 2000, p. 298). In other words, initial premises may take whatever form the discussants perceive to be the most defensible and readily acceptable by the other discussants even if they have no basis in fact. The opening stage is very important because it not only marks the beginning of argumentation, it sets the tone for that argumentation. Initial premises strike a balance between their acceptability and their ability to lead towards a meaningful resolution. In design, for example, a resolution must be both acceptable and actionable.

A good example of early premises that could be categorized as an opening stage comes from the early discussions of a design team (Bucciarelli, 1994). The group of engineers was developing criteria to measure their design against. A widely agreed-upon premise (criterion) was that their completed design "does the job" (ibid., p. 153).

Although it is appealingly succinct, *"does the job"* is not remotely specific enough to provide insight into necessary qualities of the design, nor is it a criterion that can be measured against. However, in the PD sense, this opening premise can be useful. First, it marks a status of agreement among the discussants and perhaps a willingness to agree. Because they are not directly at odds with one another, they can proceed in their discussion by offering argumentation about what it means for their design to "do the job" and how they can determine if it is "doing the job" successfully. The next step, which they do, is to clarify and refine this premise into measurable criteria. That clarification may involve better verbalization, or it may include nonverbal means.

Argumentation Stage

In the Argumentation stage, protagonists and antagonists proceed by adducing arguments for a standpoint and providing critiques of those arguments, respectively. In PD, argumentation can be both explicit and implicit. In fact, discussants are responsible for both forms of argumentation, and both forms can be challenged. "[E]lements of the argumentation that the speaker does not explicitly put into words may still be part of the attempt at justification or refutation that takes place in the argumentation" (Van Eemeren, 1982, p. 119). Such implicit elements of argumentation are classically referred to as *tacit premises*, but Van Eemeren refers to them as *unexpressed premises*. The inclusion of tacit premises in argumentation comes in recognition of forms of everyday conversation. "Very often it is completely unnecessary (and thus even disruptive) to explicitize exactly what one means" (ibid., p. 119).

Tacit in reference to premises is akin to *tacit* in reference to knowledge. In both contexts, *tacit* refer to that which is known but not said. Although it is not the case that "what is left unsaid is fundamentally unsayable," (Duguid, 2005, p. 110), it *is* the case that people often deliberately choose, for the sake of clarity, not to explicate every component of their statements. Explication may be too difficult or simply too cumbersome to enhance communication. In PD, discussants are responsible for ideas they attempt to convey but choose not to explicate. Hence, knowledge held within the tacit dimension can be considered valid support for argumentation or criticism thereof. Tacit knowledge may be alluded to by tacit premises.

Concluding Stage

In the Concluding stage, argumentation ceases based upon the previously established (often tacit) agreements made by the discussants. There are two possible outcomes: 1) the standpoint is accepted because the antagonists withdraw their critiques; 2) the standpoint is withdrawn by the protagonist in favor of the critiques against it. At this point, the discussants can either move to a different standpoint, or continue discussion around a modification of the original standpoint. In either case, further discussion will proceed through all four stages from *confrontation* to *concluding*. This process presents the discussants with another opportunity to assess the constellation of standpoints in light of new information and discoveries made in recent argumentation.

APPLYING PD THEORY TO THE DESIGN DISCUSSIONS AT HAND

The previous exposition of PD theory has been, in part, to demonstrate that the theory contains no a-priori theoretical disqualifications that would prevent its application to a design discussion. I conclude that PD theory certainly *could* apply. How to apply it and whether such application will prove useful remains to be seen.

Research Question 2: How can pragma-dialectic theory be applied to understand these (emergent argumentation) characteristics? is not only about the discussions of the students in this study; it is a first pass to determine if PD theory might be useful for design deliberations in general. PD theory is large and complex, and there are many potential ways to use it as an analysis framework. For this first pass, I have chosen to see how the four stages reveal themselves in the students' discussions and if those revelations suggest opportunities for discursive scaffolding. This is one way of using PD theory as an analytical tool in order to inform its potential use as a normative guide later.

CHAPTER 3: METHODS

RESEARCH QUESTIONS

In this chapter, I delineate the research methods employed to address my research questions. I will refer to the following more specified form of the questions as they were informed by the literature review.

1) What characteristics of argumentation emerge from students' design conversations?
2) How can pragma-dialectic theory be applied to understand the argumentative characteristics of student design discussions?
3) How do the students use their own tacit knowledge and objects to resolve design challenges, and how does their tacit knowledge relate to their argumentation practices and team design efforts?

PARTICIPANTS AND SETTING

The setting for my study is a Central Texas high school robotics class taught by Mr. John Sperry.[7] The course provided several affordances for the study. First, the course included a semester-long project that allowed many days for students on the design teams to resolve differences of opinion concerning robot design and the implementation thereof. Second, the course offered a design challenge that was difficult enough to warrant having temporally separated teams (e.g., the teams were from four different sections, and hence class times, of the same course) collaborate on the same design (described below). Third, robotics is compelling for many high school students, and this was an elective course, so it was probable that the students would be engaged in the project. Fourth, all the students were engineering design novices. Most aspects of engineering design were new to these students, including robotics, computer-aided design (CAD) software, and team design. With design as a component of introductory high school engineering courses, I believe it's important to study how students react when asked to solve complex design challenges. I wanted to characterize the discourse that inexperienced students brought to

[7] Mr. Sperry's name is used with express written consent.

an engineering challenge in order to inform the eventual design of learning scaffolds that honor student (novice designers') design strengths and address their weaknesses.

In the spring 2010 semester, Mr. Sperry taught four sections of Robotics I. For the students, this was the second semester of a one-year course that began in fall 2009. The four sections together totaled more than 100 students. All four sections participated in the same robotics challenge. The high school that hosted my study operated on a block schedule, which meant that each class met every other day—3 days in one week, 2 days in the next. Each class period was about 90 minutes. For my study, I chose student groups from two sections, period 3 and period 5, both of which met on the same day, and groups from periods 2 and 8. Period 3 and period 5 had a combined total of 51 students, 12 of whom were female. The students were in 10th, 11th and 12th grades. Periods 2 and 8 had similar demographics.

During the 2009–2010 school year, this high school was labeled "Recognized" by the Texas Education Agency according to federal No Child Left Behind guidelines. "Recognized" means that 75% of the school's students passed the Texas Assessment of Knowledge and Skills (TAKS)[8] and State-Developed Alternative Assessment (SDAA) II state exams, 85% of the students completed or were continuing their education four years after entering the school, and 0.7% or fewer dropped out. In 2010, the school had a total of 1,997 students: 1,192 white, 506 Hispanic, 173 African American, 119 Asian, and 7 American Indian (Schooldigger.com, 2012). The selected focus classes for this study reflected this population distribution with some skew towards a greater proportion of white students. These population and accountability data are meant only as descriptors. In this study I do not account for demographics or relate the study results to student achievement. The relevant characterization is that this was an above average-performing high school not beset with unfair financial and social challenges all too common in today's education system.

Mr. Sperry participated in the UTeach Engineering (Farmer et al., 2012) teacher training program in 2009. That cohort of high school teachers included, in my opinion, the finest STEM educators this town had to offer. Each one of those teacher's classrooms

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[8] Since that time, Texas has replaced the TAKS with STAAR—the State of Texas Assessments of Academic Readiness.

was worthy of study, and in my role as a research assistant for the UTeach program, I had the privilege of getting to know them and observing some of their classes for other projects. I approached Mr. Sperry for several reasons: 1) He was very receptive to having me observe his classes in the role of researcher. 2) His robotics classrooms appeared to be the most student-driven out of all the classes I had observed. In fact, a novice observer might characterize his robotics classes as chaotic, but such a characterization would be belied by the depth of Mr. Sperry's classroom management experience and his emphasis on safety, respect, personal responsibility, and collegiality as required—and regularly reinforced—values in his classroom culture. 3) The school at which Mr. Sperry taught offered a high probability of a good return on signed consent forms. Besides, Mr. Sperry and I had good rapport, and the situation just worked out well.

Participant Consent

All parents, or students of consenting age, consented to participate in this study. The consent forms came from the UTeach Engineering Protocol #2008-03-0060.

Design Challenge

The competitive robotics challenge Mr. Sperry and I devised involved designing two robots to operate on a specially designed apparatus (Figure 3-1). One robot was to move along one of the two horizontal rails, collect balls from the shelf, and then drop them to a second robot waiting on the floor below. The second robot was to receive the balls and then launch them between two goal posts (the legs of the apparatus) to score points. Each pair of robots, one on the rail and one on the floor, would act as a team; each pair was to be designed by students working collaboratively, and two robot teams would compete simultaneously.

Photograph 3-1: Robotics Challenge Apparatus

Challenge Instructions

The following instructions were given to the students at the beginning of the challenge.

Robots

1) Pickup and Dropoff: This robot must move along a 3" diameter tubular rail that is approximately 7 feet long. This robot must also collect 4" diameter balls which rest on a shelf just below and to one side of the tubular rail. These balls will rest 6" apart as measured from the center of one ball to the center of the next (6" on center). Additionally, a third row of balls will sit in the middle of the shelf. These balls will be placed at varying heights. Each ball must be delivered to a launcher robot positioned on the ground about 5' below the tubular rail. The position of the launcher robot is fixed.
2) Catch and Fire: This robot rests on the ground and receives balls dropped from the Pickup and Dropoff robot. Catch and Fire must then shoot the balls through a specified target zone, black balls to the black target and green balls to the green target.

Game Specifics

- You will be able to control your robots manually at first, but by a specified date (TBA), each robot must operate autonomously.
- You may use additional materials to build your robot.
- Points:
  - (1 pt.) Ball picked from shelf and dropped
  - (2 pts.) Ball picked from shelf and dropped into Catch and Fire robot
  - (1 pt.) Ball launched through target
  - (2 pts.) Ball launched through target of correct color
- Pick-up and Drop-off
  - Pieces of tape along the tubular rail will coincide with the center of the balls on the shelf.
  - Balls must be dropped *without stopping the robot.*
  - Robot can be designed to fit completely around the 3" diameter tubular rail, if desired. Game apparatus will be disassembled to accommodate this.
- Catch and Fire
  - Robot rests on the ground, and its position is fixed.
  - Robot must fit within a box measuring X x Y x Z.

Teams

You will work in a team of 4-5 students designing one of the two types of robots. Your team will need to coordinate its efforts with other teams in your class as alliance members during game play. Cooperative strategies, alignment of designs and communication between robots may all be things for your team to think about and discuss.

Figure 3-2: Design Challenge as Presented to Students

Designing the Design Challenge

When designing this challenge, Mr. Sperry and I two goals in mind. First, we wanted to explore the limits of student design capabilities in a first-year robotics classroom, and second, we wanted to simulate the experience of engineering designers who work in geographically disparate teams—a separation that places high demands on communication abilities. We addressed the first goal through the game challenge described above. Our challenge expanded on requirements typically found in TETRIX (http://www.tetrixrobotics.com/Competitions) robotics competitions by incorporating motion along a rail, targeting and shooting balls, and the requirement of an alliance between robots with separate functions.

We addressed the second goal by requiring that a group from period 3 partner with a group from period 5 to design and build a single robot, either the rail model or the stationary model. Since all class periods worked in the same classroom, this separation wasn't exactly geographic, but it did significantly restrict the ability for the partnering groups to communicate face to face directly. Professional engineering designers often work at a distance, and in doing so tend to rely heavily on electronic communication (Leonardi and Bailey, 2010; McNair and Paretti, 2010). In fact, engineering colleges are currently experimenting with design classes that incorporate real geographic separation within design teams.

The setting for my study provided an opportunity to see how high school students cope with analogous separation challenges. Students within a particular class period could talk face to face, but they would have to share ideas and coordinate with their partners in the other class period electronically (Figure 3-2). Typically, period 3 students would come to class, work on the design, and post online notes to period 5. Then period 5 students would come to class, read the posts, and pick up where period 3 left off…at least, in theory.

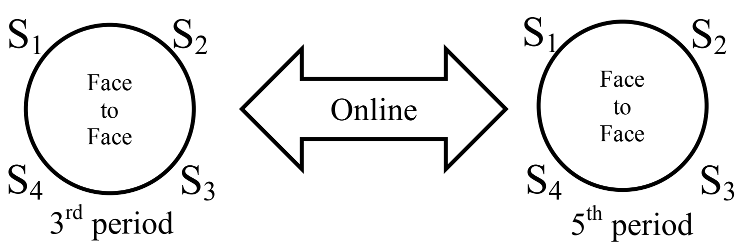

Figure 3-3: Communication Between the Two Class Periods of a Single Team

All online communication was recorded in Google Docs, which we chose in order to preserve a record of the student groups' entire discussion. For grading purposes, Mr.

Sperry required one substantial post per student per day. Before the two different section groups teamed up, Mr. Sperry told each class that their posts should be relevant to their discussion and that they should try to be helpful and offer constructive criticism. He did not prepare them with specifics on communication approaches or structure. As long as each student tried to make his or her contribution relevant, they were free to post whatever they wished.

We intentionally did not provide the students with extensive scaffolding to support their overall design process. The semester-long challenge was broken down into two main stages: 1) brainstorming and CAD, in which periods 3 and 5 worked separately, and 2) discussion and assembly, in which the teams (e.g. Rail 1, Stat 1[9]) began communicating online across class periods. Their subsequent face-to-face and online discussions might include further brainstorming, but it was not a class activity per se. Class period groups were formed at the beginning of the CAD stage. From then on, each team had to work according to its own schedule. Various kinds of support were provided largely as needed by Mr. Sperry, me, a student aide, and visiting upper-level robotics students. The support we provided was largely unstructured, and intentionally, we did not limit participating students' ability to seek assistance. We encouraged them to help each other and to ask questions of anyone they believed might be of assistance. For a more detailed timeline of the work carried out over the semester, see Appendix A.

RESEARCHER ROLE

It was the particular nature of Mr. Sperry's robotics classroom that intrigued me. Here was a group of high school students, who, for probably the first time in their school careers, were given a compelling, yet daunting, task, and asked to figure it out for themselves. They were encouraged to employ whatever knowledge and know-how (Cross, 1982) they had at their disposal. They worked in teams, but they were not doing "group work"—a phrase that was met with disdain whenever I brought it up with students. They had a design challenge they needed to accomplish with only a large store

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[9] There were two types of robots: *Rail* robots that moved along the horizontal pipe collecting balls, and *stationary* robots that received and shot balls. Thus Rail teams made rail robots, and Stat teams made stationary robots.

of parts, their wits, and each other. This classroom was like no other they had ever experienced. They knew it, and they relished it.

I worked in the classroom as a researcher-facilitator, with an emphasis on facilitation. Despite my cameras, microphones, and almost daily presence, I wanted the students to be comfortable with me and see me as an ally. Also, as an educator, I could not just sit there day after day, watching them. I had to be helpful. However, I didn't want to unduly influence their ideas with my own, so I was cautious with my assistance. Typically, I would help look for parts, help keep the classroom organized (a losing battle), troubleshoot computer problems, and make some suggestions as long as they were in support of *the students' ideas*. Rather than answer questions, I would usually try to find another student or team that could be helpful.

In my exploration of this environment, I selected an array of potential methodologies that might provide answers to my research questions. These methodologies included conducting close observation, analyzing video recording, and analyzing online discussions. Each method brought with it affordances and complications that eventually led me to focus on the teams' online discussions.

DATA SOURCES

	Name	Description
✔	**Online Discussion Records**	6 online discussion threads, 1 per team, 6,240 average word count per discussion; each discussion lasted 12 class days.
✔	**Close observation notes**	~20 pages total
✔	**Design Team Video**	Two teams, Rail 1 and Stat 1 Rail 1: 21 videos; ~9h, 30min Stat 1: 7 videos; ~6h
✔	**Design Proposals**	12 collected total, 2 from each team Rail 1, period 3: 733 words, 3 drawings Rail 1, period 5: 649 words, 0 drawings Stat 1, period 3: 694 words, 4 drawings Stat 1, period 5: 650 words, 0 drawings
✖	**Student interviews**	Rail 1: 8 individual, ~8min each Period 3 and period 5 group, ~5min each (total of 8 students) Stat 1: 8 individual, ~8min each Period 3 and period 5 group, ~5min each (total of 9 students)
✖	**Final Presentations**	Rail 1: 13 slides; periods 3 and 5 presentations video recorded Stat 1: 13 slides; periods 3 and 5 presentations video recorded All other period 3 and period 5 teams video recorded.
✖	**Early design sketches**	6 drawings, various teams
✖	**Functional Requirements**	1 spreadsheet per student, aggregated and edited by Mr. Sperry and myself
✖	**Project Survey**	50, one for each student in period 3 and period 5

Table 3-1: Data Sources

All data sources are listed in Table 3-1. Making sense of the learning environment under study—through the lens of argumentation—was not unlike solving a design problem. The environment presented myriad complex inputs, all of which held potential for providing valuable insight. As a novice researcher, I found many aspects of this classroom to be nonroutine. In such an environment—one that presents many complex inputs—intuitive thinking is a powerful sense-making strategy (Pretz, 2008); therefore, I decided to capture a wide range of data to support subsequent extraction of those data that were most suitable for analysis.

While observing the classroom and perusing the literature, I would develop the specific expertise necessary to move from an intuitive problem solving approach to a more analytic approach. During that process, I wanted to ensure that I had not neglected important data. Hence, I cast a wide net. As my expertise developed, I selected the following data set for analysis: online discussion transcripts for six design teams, classroom video of two design teams, observation notes, and design proposals from the two videoed teams. The challenge of my methodology was to move from intuitive impressions to justified reasons based on analysis without losing sight of meaningful intuitive insights—to balance both intuitive and analytical modes of thinking.

I will now describe the affordances and liabilities of the selected data sets, and then, more briefly, describe why I did not choose the others.

Online Discussions

As the semester evolved, and various methodological problems emerged, I decided to focus my analysis on the online discussions. Unlike close observations or video, these discussions offered a daily record of the students' design interactions from beginning to end. Design moments that occurred during face-to-face interactions wouldn't necessarily be explicitly captured in their online text, but the occurrence of these moments, and traces of their results, was at least implied in the posts. Further, the online discussions required that students articulate ideas beyond the level of what the students might choose to say face to face. This level of articulation would undoubtedly support my search for traces of argumentation within their discourse. Given the nature of this classroom environment, I came to believe that the students' online discussions were the best way to provide insight into what the students were thinking and how they resolved their differences. The analysis methods in this chapter focus on how I examined records of their online discussions to seek characteristics of argumentation (research question 1).

With the online discussion records, in contrast to the classroom video, the students' statements were complete; they could not talk over each other; there was no background noise; and because they could not point to some object as a substitute for words, they had to write their ideas as clearly as possible. The online discussions were also useful in light of the fact that one of the biggest communication challenges faced by engineers is their ability to explain their ideas clearly in regard to the needs of their audience (cf. Leonardi and Bailey, 2010; Sageev and Romanowski, 2001). The online discussions afforded me the opportunity to examine the discourse moves of novices as they tried to explicate their knowledge, tacit or otherwise, as clearly as they could.

Close Observation

I was present in Mr. Sperry's classroom twenty-four of the fourty-nine A/B block schedule class days of the Spring, 2010 semester. My absences on some days were unavoidable due to my other student and research commitments. While I was in the classroom, I learned important features of the students' day-to-day activities—and that my observation notes alone were not going to provide me the data I needed to answer my questions.

The room was cramped. Movement to and from the parts bins as well as general navigation was restricted. The students had little space to move in which to have engagements common to design teams (Radcliffe, 1996). Typically, they had to go to the parts bins, select what they thought they needed, and return to their team's work area, also small and cluttered with laptops, cables, etc. These restrictions made it difficult for the students to convene around the parts bins, for example, and have exploratory discussions on how to use the parts they had available to reify their design vision. Engineering design is often a compromise between what the designer wants to create and the resources available to create it (cf. Dorst, 2006). The conditions of the room made it implausible for me to track even a single team's design progress as they moved about the room. Some teams were physically isolated by tables, chairs, and other students. In order to be within earshot and to hear their communication, I had to be right on top of them, which was unreasonably intrusive. They had enough trouble finding space without accommodating me.

Within these constraints I observed a pattern of work that consisted of long periods of mostly nothing (observable), peppered by short, intense periods of active engagement. Much of their time was spent sitting quietly and looking confused. Between their sporadic visible work bursts, and cramped and crowded quarters, important moments in their design process were easily missed, or if I saw them occurring, I was often unable to get close enough in time to hear what the students were saying. In short, the activities within the physical space were impossible to track with sufficient detail.

On the other hand, my presence allowed me to see promising aspects of their work environment. Overall, they were collegial and mutually supportive of each other's work. They assisted each other on short notice, provided advice, lent tools, and offered encouragement. "Aaron!" they all shouted in concert, as they welcomed their teaching assistant into the room. This greeting happened almost every day. It suggested to me a strong cohesion among the robotics students as well as a sign of appreciation and respect for this upper class student. He was very helpful, and they welcomed his advice, which often came in the form of demonstrations with parts on how best to fit them together to perform a specific task. I witnessed these interactions most often at a distance. Likewise, the students provided demonstrations for each other, and these demos showed me that their design communication was largely gestural and reliant on physical artifacts. Sometimes the students would convene around the game apparatus to size up their robot. Again, I captured these moments as best I could. Though interesting, these moments were isolated, not contextualized by that team's overall process. All told, though, the students appeared engaged.

That said, the close observation contributed to my analysis of the online discussions in important ways: 1) In class, the students worked together and developed their ideas in collaboration with one another. I anticipated that this behavior would emerge in their online discussions—that important contributions would come from many team members. 2) In class, the students relied heavily on gestures and physical objects to communicate their ideas. It seemed reasonable, therefore, to surmise that they would find ways to bring other modes of communication into their online written communications. In other words, they might find ways to replace the communicative acts of pointing, or providing demonstrations. 3) It also seemed reasonable to expect that the sporadic nature of their work would be reflected in their online discussions.

When studying cross-site communication patterns, which this study resembles, it is important to understand work and communication patterns at each site (in my study's context, class periods) (Leonardi & Bailey, 2010). My close observation of the class periods served as a starting place for my interpretation and understanding of the students' cross-class communication.

Design Team Video

Given the difficulty with close observation, I sought to use video recordings to capture all the "design moments" of two teams. Again, to understand how their communication supported their design negotiations, I needed to be able to track a team's design process from beginning to end. Design interaction studies had been done based on video, but because in those cases the recording was done in a controlled environment (i.e., closed room or studio), the researchers had complete and clean data (Brereton, 2000; Dixon & Johnson, 2010; Dorst, 1996). My video data was neither clean nor complete. Students talked over one another, and even the localized table microphones were often unable to capture the students' speech above the noise. Also, students would have conversations and demonstrations off camera. I was not there every day; hence, neither were the cameras. The point is that video recordings were not able to provide me with a solid corpus of vocal interactions from the beginning to the end of the students' design process. Thus it was not feasible to capture their argumentation patterns from their face-to-face encounters.

The recordings I collected did provide some insights, however. 1) They confirmed my observation of long moments of low visible activity, peppered by short moments of intense activity. Important design moments were present, but fleeting. 2) I saw various physical demonstrations as students attempted to communicate their ideas to each other. The demonstrations were highly gestural (e.g., pointing), incorporated physical objects, and included lots of pronouns. This data showed me that students' face-to-face communication was multimodal, and that—based on the lack of specificity of the pronouns contrasted with the specificity of the physical objects—words were not necessarily functioning as the primary mode. This finding aligns with existing research on designer interactions (Harrison and Minneman, 1996; Radcliffe, 1996). Further, the video data provided me with images of the objects that students referenced in their online discussions.

Design Proposals

Each student group from period 3 and period 5 created a design proposal for either a Rail robot or a Stationary robot. Groups were allowed to choose which style of robot to design. We needed equal numbers of Rail and Stationary groups in both class periods, so the students' choices were enacted through a voting system. Each design proposal was to follow a set of parameters created by Mr. Sperry and myself (see Appendix D), and the students submitted proposals to Mr. Sperry. From there, Mr. Sperry and I matched groups from period 3 and period 5 based on the content of their proposals. We tried to align groups with similar proposal ideas in order to help facilitate collaboration of teams across class sections. We predicted that the students would have to resolve differences of opinion even between proposals eliciting similar concepts. We feared that, faced with two radically different proposals, the students' differences of opinion would become impasses which the students would not have enough time to resolve. We suspected that differences of opinion (of one form or another) would arise even after a team came to an agreement on a single design.

The online discussions began after two groups (one from period 3 and one from period 5) exchanged design proposals and had one day to review them. For example, team Stat 1 had to resolve the differences between two differing design proposals in order to create a single robot.

DATA EXCLUDED FROM ANALYSIS

Student Interviews

I conducted student interviews to get a sense of how they were responding to the design challenge. During the challenge, I spoke with individual team members in a separate room. The interviews were filmed. The questions focused on the student's experiences with group work in Mr. Sperry's class and in other classrooms. My intention with the interviews was to determine how the robotics design challenge motivated students' "need to know" (Berland & McKenna, 2010; Scardamalia, 2002); specifically, how the challenge motivated their need to value the input and collaboration of their partner design team from another class period. The interviews provided some useful insights, but ultimately did not prove to be clear windows into the students' peer interactions. I chose not to do member checking to verify the meaning of some of their online statements because I wanted to avoid influencing their communication in this way. My presence in the classroom was already influencing them. For example, the "grip tape" that Rail 1 liked so much was actually my suggestion to them. I wanted to examine their discourse as it evolved on its own, so I avoided asking them to comment on it.

After the challenge was completed, I spoke with the Rail 1 team and Stat 1 team from each class period (period 3 and period 5)—four interviews in total. I asked them the following open-ended questions:

1. Why did we set up the communication structure like we did?
2. Why did we design the challenge like we did?
3. What was the hardest thing about this project?

I wanted their honest, overall impressions of the semester, so I used questions that were open enough to promote some discussion.

Final Presentations

Final oral presentations for teams in periods 3 and 5 were video recorded. Their presentations were prompted with a rubric of topics to address in their slides and class-period team presentations (See Appendix G). The topics focused more on their design than on their communication. There was to be a final report as well, which did ask the students to reflect on their communication; we did not assign the report, however, because there was not enough time left in the semester.

Early Design Sketches

Early in the semester, the students were asked to create hand-drawn sketches of some design ideas for either the rail robot or the stationary robot as part of an early brainstorming exercise. The overall quality and detail of some of these drawings helps to support the students' expressed preference for using drawings that are actually useful. Looking back over the semester challenge, I agree with the students that their paper drawings may have been a more useful tool for them than were their CAD drawings. However, I excluded these early paper drawings from the analysis because these drawings occurred during early brainstorming activities prior to the formation of the Rail and Stationary robot groups.

Functional Requirements

Also formulated early in the semester, functional requirements were devised by the students as design criteria against which their designs could be tested, e.g., “gripper works quickly” for Rail robots, or “dropped balls must not bounce out” for the Stationary robots. The students also came up with functional requirements related to sensors and programming. However, measuring their design against the functional requirements was an analytical task that required a working robot. The teams did not get that far along. Furthermore, during the online discussions, the teams rarely referred to the functional requirements explicitly. This fact was not surprising, as the functional requirements, except for those related to programming, were not themselves very specific, so these requirements would offer little specific design guidance. Tables of the functional requirements for Rail robots and Stationary robots are given in Appendix C.

Project Survey

The project survey was a seven-question Likert-scale survey given during the time of the students’ final presentation. If I were to attempt an asynchronous design project in school, or if I were advising a teacher, I would examine the survey. For this dissertation, it did not help me analyze the students’ online discussions or answer my research questions. [Appendix H]

Analysis Methods (Overview)

My analysis proceeded through an iterative five-step process. I will list the steps, and then I will explain each in greater detail.

1. **Read the transcripts:** I read the team online discussions carefully to get the shape of the data and look for communication trends. I also examined classroom video, classroom observation notes, and interview responses.

2. **Create the coding scheme:** I developed a coding scheme for classifying statements by type, as defined below.

3. **Determine and graph code distributions:** I counted the frequencies of the codes for each team and across all six teams, and presented them in graphical form.

4. **Graph the timeline of coded statements for each team:** For teams Rail 1 and Stat 1, I created timelines of all coded statements.

   Results from step 3 and 4 are found in Chapter 4, Section 1.

5. **Four stages of resolving a difference of opinion:** For teams Rail 1 and Stat 1, I classified particular statements as indicators of the four stages of a critical discussion, according to PD theory: Confrontation, Opening, Argumentation, and Concluding.

   Results from step 5 are found in Chapter 4, Section 2.

6. **Use of tacit knowledge and physical objects:** I then reviewed the results from the descriptive analysis and Pragma-dialectic analysis to find specific ways in which use of tacit knowledge and objects emerged in the online discussions of teams Rail 1 and Stat 1.

   Results from step 6 are found in Chapter 4, Section 3.

7. **Cross-check analysis of team Rail 4:** Unlike Rail 1 and Stat 1, Rail 4 possessed detailed and serviceable drawings of their robot. This unique situation provides an opportunity to check against the results from Rail 1 and Stat 1 analysis. I will

perform abbreviated descriptive analysis similar to steps 3 and 4, and I will then repeat step 6 for the team Rail 4. This step will serve to understand what effects possession of high quality drawings may have had on argumentation patterns and the use of tacit knowledge and the physical object.

Results from step 7 are found in Chapter 4, Section 4.

Analysis Methods (Specifics)

STEP 1: READ THE TRANSCRIPTS

The first step was to familiarize myself with the data. This meant reading each online discussion several times in order to get an idea of each team's story. During that process, I made notes, highlighted recurring themes, and began to define the structure of a useful coding scheme. I considered both delineations based on syntax (Fahy, 2000; Hillman, 1999) and delineations based on units of meaning (Henri, 1991, as cited in Rourke, Anderson, Garrison, & Archer, 2000).

Each transcript contained, by design challenge requirement, at least one *substantive* post from each team member for every class period. The transcripts were a record of the portion of the challenge in which the two separate class periods (third and fifth periods) were actively collaborating. This portion lasted 12 class days. The transcripts were lengthy, and I revisited them several times throughout the analysis process. I also looked through the video records associated with a particular discussion for relevant face-to-face interactions in order to get a better idea of how the students' ideas were developing and, more importantly, to get a look at the physical objects referenced in their transcripts.

STEP 2. CREATE THE CODING SCHEME

Final Coding Scheme: Discourse Codes

Exemplar statements and detailed descriptions for each code are listed in Appendix F. A description of how this coding scheme evolved is given later in Chapter 3.

Code Name	Description
Design Elements	Any reference to specific design elements or reference to the overall design. The elements can exist as ideas or as attributes of a physical object. Design elements include descriptions, explanations, suggestions for modification, etc.
Drawings	Any reference to the drawings or design proposal.
Object	A reference to a physical object that is used as an explanatory device.
Assigning Tasks (Task)	A statement that describes a specific action item. Typically, "we will" or "you will." May appear in the form of a question.
Progress Report (PR)	A statement describing what a team has done.
Team Dynamics	Statements that address problems or voice concerns about issues of team collaboration. May include personal complaints and accusations.
Praise	Favorable descriptions of the robot, statements of a job well done, encouragement.
Mr. Sperry	An instance when a student references Mr. Sperry
Agreement	An instance when one team member explicitly agrees with another or more than one other team member.
Questions	Direct requests for information or explanation.
Answers	Responses to previous questions. Statements are not coded "Answers" without a preceding question.
Inviting Ideas	A statement that solicits ideas from an individual or the team members at large.
Inviting Questions	A statement that invites questions for further information or explanation.

Table 3-2: Discourse Codes

Table 3-2 describes the types of statements the students were making. To preserve my objectivity, I wrote down strict definitions for what statements belong to which Discourse Code. Once the list was established, statements that fell outside of all definitions were not given a Discourse Code. Such statements may have been assigned to one or more (robotic system) Subsystem Codes, defined below.

The Discourse Codes Fall within PD Theory

According to PD theory, argumentation is a complex speech act which is itself a constellation of other speech acts. Van Eemeren and Grootendorst (2004) lay out which speech acts appear in the four stages of a critical discussion (p. 67). Table 3-3 is an extension of their table and includes my discourse codes for reference. The purpose of Table 3-3 is to demonstrate that my coding scheme is "in-bounds" with regard to PD theory. In other words, my codes can be categorized as one or more of the speech act types used by PD; therefore, my codes, as representations of discussion statements, have a role in the resolution process outlined by PD.

I applied my codes based on the most apparent intention of the statement, as I perceived it. For example, *Design Elements* statements have the intention of describing some aspect of the design, either physical or conceptual. *Mr. Sperry* codes have the intention to invoke the words, direction, or advice of the teacher. As such, each code can, depending on context, have additional intentions. For example, "[Mr. Sperry] told us to do this" would be a directive for the entire team; whereas, "[Mr. Sperry] explained it like this" would be a usage declarative. Additionally, "it's clearly doesn't work" is Design Elements and also an assertive; whereas, "it doesn't work because the wheels are too far apart" is Design Elements and also a usage declarative. Also note that I placed *Praise* as an assertive. I did this because a statement like, "The robot looks great!" is certainly an expression of a psychological state of happiness, approval, etc., but it is also a statement of truth in the sense that the current "great" state of the design has tacit appeal. The current state aligns with the speaker's mental representation, so from an intuitive perspective, "looks great" is an assertion of truth and a commitment to that truth. As expressives, Praise statements don't officially play a role in the resolution process, but they can play an important role in guiding the conversation.

PD Stage Name, Number		Assertives	Commisives	Directives	Usage Declaratives	Expressives
Confrontation	I	✔	✔	✔	✔	✖
Opening	II	✖	✔	✔	✔	✖
Argumentation	III	✔	✔	✔	✔	✖
Concluding	IV	✔	✔	✔	✔	✖

PD Stage	Associated Speech Act and Code Names
I, III, IV	**Assertives** "commit the speaker to the truth of the expressed proposition" (Searle, 1976, p. 10)
Code Names	Design Elements, Drawings, Object, Answers, Progress Report, Team Dynamics, Mr. Sperry, Praise
I-IV	**Commisives** "commit the speaker to some future course of action" (ibid., p.11)
Code Names	Assigning Tasks, Mr. Sperry
I-IV	**Directives** "attempts by the speaker to get the hearer to do something" (ibid., p.11)
Code Names	Assigning Tasks, Questions, Inviting Ideas, Inviting Questions, Sperry
I-IV	**Usage Declaratives** a "definition, specification, amplification, etc.," clarification (Van Eemeren, 2004, p.67)
Code Names	Design Elements, Drawings, Object, Answers, Mr. Sperry
None	**Expressives** demonstrate the psychological state (of the speaker) regarding the current situation (Searle, 1976, p.12)
Code Names	Praise, Team Dynamics

Table 3-3: Speech Acts and Discussion Codes

Statement Length and Multiple Codes

In choosing appropriate statements to code, I took inspiration from methodologies in studies on asynchronous online interactions (see Rourke, 2001, for review). Electronic notes, similarly to written letters, substitute for face-to-face communication; therefore, electronic text often reads like spoken language (Davis & Brewer, 1997). The students' posts in this study were no exception. In analyzing and coding written text, one option is to use a sentence as the desired length for statements (Hillman, 1999). On the other hand, since the text reads like spoken word, another option is to choose statement length based on the illocutionary act or the intention behind the statement (cf. Searle, 1976; Van Eemeren, 1984, 2004). This strategy was introduced by Howell-Richardson and Meller (1996) to study student interactions in computer-mediated courses.

I chose a combination of strategies by selecting statements no shorter than one sentence and sorting them according to their underlying intention. This method aligned with PD theory since all utterances are assumed to be speech acts. It also served the practical purpose of not trying to manage very short statements. I diverted from Howell-Richardson in that my codes did not use terminology commonly associated with illocutionary acts, i.e., *interrogative*, *declarative*, etc. Rather, I chose coding terms that were more indicative of team design interactions.

Individual statements sometimes conveyed multiple intentions, and thus received multiple codes. For example, I coded this statement—"I really like how the arm works with the gears, but it's not fluid, how can we fix this?"—as Questions, Agreement, and Design Elements. The how to "fix this" query is a Question; "Like" expresses the Agreement, and the observation on fluidity is a Design Element.[10] The entire sentence could have been parsed into three statements, coded independently, but the contextual meaning of each depends on the others. The statement has more meaning taken as a whole, so it was better to assign it multiple codes.

Parsing the Transcripts (Member and Subsystem Codes)

For tracking purposes, I parsed each team's transcript with the following codes.

Team Member	A team member code assigned to each discussion post by a given team member. Thus, a post written by student A was coded "A."
Third or fifth period	Team member codes aggregated into their respective class periods.
Subsystem	Any reference to a specific robot subsystem. To warrant a code, a specific subsystem had to be mentioned in about half of a given team's posts.

Table 3-4: Member and Subsystem Codes

While reading the transcripts (Analysis Methods, Step 1), I noticed that the student teams all discussed a few select robot subsystems extensively. I decided to separate each transcript into smaller discussions according to the particular subsystem at

[10] "Really like" could have implied a Praise code; however, the tenor of the statement in context leaned more to Agreement than Praise. This is an example of a possible coding dispute that may have been resolved by employing a second coder.

hand. Subdividing a system into subsystems is common (and arguably necessary) in engineering design, and these students were encouraged to do so. However, how they determined one subsystem from another was entirely up to them. In order to qualify as a subsystem discussion, that subsystem had to be mentioned in about half their posts. That qualification exists because I wanted each subsystem discussion to have relevant bearing on the design itself. Not all subsystem discussions did. For example, each team discussed writing a program to control their robot; however, no team had time to write a program. Hence, programming did not qualify as a relevant subsystem.

A single statement could also be part of more than one subsystem discussion. The following was coded both *Funnel* and *Arm*: “Yeah the funnel and arm will need some tinkering but in general the funnel is going to lean away from the ball mount so it doesn't run into anything.” The statement has more to do with the Funnel than the Arm, but keeping them together helped demonstrate that the students saw the two subsystems as closely related.

The Discourse Codes in Table 3-2 are based on the character of a particular statement. These codes may apply to the overall situation, or they may apply to certain aspects of the design and not to others. For example, a team may have made *Progress Reports* with regard to only a particular subsystem, while mostly asking *Questions* about a different subsystem. The students’ design discussions were broken down into subsystem discussions. My ability to associate Discourse Codes with Subsystem Codes let me analyze the students’ design resolution process at the subsystem level.

Bookkeeping, e.g., keeping track of when statements were made and by whom, was an important part of coding the records of students’ online conversations. Team conversations about a design evolve over time in an iterative exchange between designers and with the object itself (Schon, 1983; Bucciarelli, 2002). Certain statements can only be made in light of previously developed information, and a statement’s meaning or value may change depending on the time and context of its utterance. Hence, capturing the temporal aspect of these students’ discussions was crucial to characterizing their argumentation structure. For example, knowing *when* Mr. Sperry statements occurred may be more valuable than knowing how many occurred. Therefore, I coded for quantity *and* for chronological placement.

I also coded each statement according to the student who wrote it. This practice let me track individual contributions—useful in my analysis even though my primary focus is on describing student argumentation at the class-period level and not at the individual level. When engineers work at a distance, it's often the case that statements or documents are primarily associated with the location from whence they came (Henderson, 1999; Leonardi and Bailey, 2008). Also, during classroom observation, I noticed a general tendency for students within a given class period to act as a team with (or against) the other class period. Characterization at an individual level would be valuable, and should be addressed in a different paper. After coding at the individual level, I decided to lump individual contributions into their respective class periods. With this sorting, each statement was made by third period or fifth period, which let me order coded statements by class period and class day, e.g. Day 1 (period 3 then period 5), Day 2 (3 then 5), Day 3 (3 then 5), etc.

STEP 3: DETERMINE AND GRAPH CODE DISTRIBUTIONS

To see what types of statements the teams made, and how frequently, I generated charts showing the distribution of discussion code (Table 3-3) frequencies: one chart for each of the six teams, and one for all teams taken together. Results are given in Chapter 4.

STEP 4: GRAPH THE TIMELINE OF CODED STATEMENTS FOR EACH TEAM

For each team, I created a chart that orders the coded statements by their position in the chronological flow of the online discussion records. These charts show the quantity and position of the coded statements, and whether a given statement came from period 3 or period 5.

STEP 5: CONDUCT PRAGMA-DIALECTIC STAGE ANALYSIS

The purpose of this analysis is to use this element of PD theory to move beyond the aforementioned coding scheme in order to describe how individual differences of opinion were actually resolved. This analysis, like the coding process, is a characterization of statements from the online discussions according to the descriptions of each of the four stages of an argument as described in PD theory (Van Eemeren, 2004, pp. 59–62). Whereas in my analysis Steps 3 and 4 (“determine and graph code distributions” and “graph the timeline of coded statements for each team”) provide information about the types of statements students use, Step 5 is meant to uncover attributes of the students’ resolution process for specific differences of opinion at the level of discussing the robots’ subsystems. It is my hope that this analysis step will reveal ways in which knowledge of the four stages of a PD critical discussion may inform useful pedagogy.

Each of the four stages of a PD argument—*Confrontation, Opening, Argumentation,* and *Concluding*—is marked by the appearance of statements that exhibit the defined characteristics of the stages. Throughout the discussion, the stages will not necessarily appear in strict linear order. In fact, analyzing a transcript according to PD theory typically involves a “transformation of permutation” (Van Eemeren, 2006, p. 13) that enables the analyst to reorder transcript statements to present the resolution process more clearly. I am valuing actual temporal occurrence of statements over clarifying the PD resolution process because my interest is in analyzing the students’ argumentation structure as it occurred. Therefore, statements in each of the stages may appear dispersed and out of order.

The online discussion statements available for the PD analysis are those from the original Google Docs which received either a subsystem or discourse code or both. Statements from the online discussion not captured by the coding scheme were not available for the PD analysis. Appendix E contains two examples of the Excel coding sheets I used. These coded statements were the candidates for assignment to one (or more) of the four stages. Once I made these Excel sheets, I did not return to the original Google Docs, except for clarification and checks for accuracy.

STEP 6: USE OF TACIT KNOWLEDGE AND PHYSICAL OBJECTS

Taking a view informed by the descriptive and Pragma-dialectic analyses, I will revisit the discussions of Rail 1 and Stat 1 in order to determine specifically how use of tacit knowledge and physical objects emerged. The purpose is to characterize how these emergent statements related to the team’s argumentation structure.

Step 7: Analysis of Team Rail 4

Unlike teams Rail 1 and Stat 1, Rail 4 possessed highly detailed and serviceable drawings of their robot. This could mean significant differences in how Rail 4 resolved its differences of opinion and referred to its physical objects. Step 7 then is a check to determine if the results of Step 6 hold for a team using high quality drawings. In this step, I will perform an abbreviated descriptive analysis, according to Steps 3 and 4, and then an analysis similar to that of Step 6, but informed by the results of Step 6.

Remarks on the Methodology

Classroom Culture

Mr. Sperry is an experienced teacher (more than 10 years at the high school level) who governs his robotics classroom with a style that appeared on the surface to approach laissez-faire. He seems to achieve this loose hand of authority by frequently expressing genuine interest in each student's success and guiding, as necessary, each student's attention back to the challenge at hand. Observations of his classroom confirmed the philosophy he described to me during a personal conversation: engage wayward students by bringing them back to the design and by helping them become excited about their own ideas. My observation, after three semesters working with him and his classes in varying capacities, is that his technique seems to be very effective. His students remained committed to long-term projects. Direct disciplinary interventions were rare.

Mr. Sperry was able to create a pedagogical environment in which the students remained engaged throughout the semester-long project. During the course of my observation semester, the students were friendly to each other, interested in each other's success, and reasonably well engaged (most of the time) in their work. The classroom was cozy. Student teams worked right next to each other, and at times workspace was scarce. Their proximity to one another often resulted in a good bit of classroom noise. However, the close-knit environment also resulted in collaboration across teams. They often provided each other with assistance in the form of technical advice, design ideas, tools, and so on. Overall, keeping students engaged did not require significant interventions. Observation suggested that the challenge was sufficiently compelling and engaging, and the students worked for their own success as well as anyone could expect of a high school class.

The influence of this school's culture on the students should not be underestimated. Mr. Sperry and this high school have been heavily involved in robotics for many years. Student teams travel to competitions; the school hosts competitions, and community members participate regularly as mentors, judges, and fans. In order to participate in competition robotics, students, teachers, and mentors must demonstrate a high level of integrity, collegiality, and cooperation. FIRST (For Inspiration and Recognition of Science and Technology) robotics refers to this as "gracious professionalism" (www.usfirst.org). Robotics at Mr. Sperry's school projects a strong ethos of learning, teamwork, coolness, and fun. For students, taking robotics classes and participation on the team are privileges. The challenge Mr. Sperry and I crafted for the students was ambitious, but we believed that they would be able to succeed.

Development of the Coding Scheme

While reading the records of online discussions, one goal was to determine a set of statement types that could encompass the bulk of the students' written conversation. I was looking for types of statements that appeared frequently and were more or less common across all six teams. PD theory recognizes the contribution of many types of speech acts to the conversation as a whole. Some speech acts can apply directly to the critical discussion, while others guide the conversation (Van Eemeren, 2004). PD places restrictions on what types of speech acts are admissible to the critical discussion, but recognizes that many other types of speech acts have important influence on the whole conversation. To honor this theory, I created a coding scheme that would describe a broad range of statement types, assuming that each type could contribute in some way to the students' resolution process. In order to determine the relative contribution of any statement type, I first had to know what types were present.

In creating this coding scheme, I intentionally departed from PD theory. I did not code for speech act types (cf. Searle, 1976); instead, I labeled statements with names that described the intention of that statement in plain English. First, my hope is that my work will be useful to engineering educators, especially robotics teachers. Making knowledge of speech act theory a requirement for understanding the kinds of things robotics students actually say is not useful (not to mention brazenly erudite).

Essentially, I developed my Discourse Codes in order to a) determine a short list of statement types that captures the bulk of the students' written design interactions, and b) see what the statements' frequency and chronological position could reveal about the nature of the students' argumentation.

Development of this discourse coding scheme took time and several iterations. Table 3-5 shows four iterations of the coding scheme. Two items are of interest.

First, *Consensus* appears in the first three columns but not the fourth. These were statements in which it appeared that the students were vying for consensus. Between scheme iterations 1 and 3, I developed Consensus subcodes, including -Teamwork, -We, -Me, -They. I intended these codes to capture the "I" statements versus "You" statements to see if the students were talking more about themselves or others. I thought that such a code might lead to an understanding of the balance or tone of the discussion. Teamwork codes captured statements referring to "us," the team as a whole. Perhaps these codes could indicate some sense of division or unity. This approach was not useful, so in the current scheme, there is no Consensus code. I dropped it because it assumed intention behind the statement. I wanted to code without such assumptions. On the other hand, I could label statements that were Inviting Ideas, Inviting Questions, or Praise without making assumptions about the student's intention behind them.

Second, *Design Criticism* and *Design Support* existed in coding scheme iterations 2 and 3 but not in the Current scheme. Again, these codes assumed the intention behind the statement. I wanted the coding scheme to be as objective as possible. I determined the various student statements' function within the discussion in subsequent analysis, as presented in Chapter 4. The objective nature of the codes provided me with one check against my own subjectivity. Labeling a statement with any of the current codes required little interpretation on my part.

1	2	3	Current
Tasks	Defining Tasks	Tasks	Tasks
Progress Report	Progress Report	Progress Report	Progress Reports
Drawings	Questions	Questions	Questions
Consensus	Answers	Answers	Answers
Questions	Consensus	Consensus:	Team Dynamics
Answer	-Inviting Ideas	-Teamwork	Explicit Agreement
	-Open for Questions	-Me	Inviting Ideas
	-Praise	-We	Inviting Questions
	Design Criticism	-They	Praise
	Design Support	Design Criticism	Drawings
	Drawings	-Criticism with New Idea	Object
		Inviting Ideas	Sperry
		Inviting Questions	Design Elements (Elements)
		Praise	
		Reference to the Object	

Table 3-5: Discourse Code History

I have included a sample of the coding tables I created for each of the six analyzed teams (see Appendix F). I used these tables extensively for creating charts, counting codes, and performing all subsequent analysis. Once these tables were created, I returned to the original transcript only as a check against possible coding errors and to recall context. Having the statements and codes in one place, I was able to recheck any previous code assignments. Creating these tables required many iterations, which gave me many opportunities to review my code assignments. Most coding errors were from oversight or bookkeeping problems. However, statements coded as Team Dynamics were often reconsidered because this was the most subjective and context-dependent code. By the final coding scheme, I resolved that Team Dynamics code should only apply to statements that describe issues (i.e. perceived problems) with team collaboration or communication. Previously, Team Dynamics codes included positive remarks regarding teamwork and communication.

For the coding process, I used the software MAXQDA 2010 (www.maxqda.com). It was useful when assigning selected statements to a particular statement type or code. I searched for seemingly common words to see how often they actually occurred. This helped me to vet subsystem codes by ranking subsystem code candidates by frequency of occurrence and then determining a cut-off value. I viewed the transcript with text highlighted by code to get some idea of the frequency and position of those codes during the process. I also exported coded statements for further analysis. However, MAXQDA did not provide the kinds of visual representations or organizational tools I wanted. Ultimately, I used Excel to conduct and document the bulk of my analysis.

CHAPTER 4: ANALYSIS

RESEARCH QUESTIONS

1) What characteristics of argumentation emerge from students' design conversations?
2) How can pragma-dialectic theory be applied to understand the argumentative characteristics of student design discussions?
3) How do the students use their own tacit knowledge and objects to resolve design challenges, and how does their tacit knowledge relate to their argumentation practices and team design efforts?

OVERVIEW

Chapter 4 contains four sections, briefly outlined as follows:

Section 1: Descriptive Analysis: Percentage of text coded per team, Distribution of codes for six teams, Distribution of code categories, Comparison of pilot and dissertation coding analysis, Code occurrence timelines for two teams, Summary of results.

Section 2: Pragma-dialectic Analysis: Evidence of the four stages of a PD resolution process is two teams' online discussions.

Section 3: Role of Physical Objects in Online Discussions: Discussion on the preferential treatment of the physical object in the two teams' discussions, A taxonomy of object-based claims

Section 4: Analysis of Team Rail 4: Brief analysis of a third team as a check against the first two teams' preferential treatment of physical objects, A trial run using object-based claims as analytical tool.

Section 5: Research Questions Addressed: Discussion on how results in this chapter addressed the research questions.

Section 1: Descriptive Analysis

Section contains results of the application of the coding scheme described in Chapter 3. Results include frequencies of all thirteen codes in the scheme for six student teams and aggregated across all six teams. Later I group those thirteen codes into four categories to form a comparison to pilot study results (Berland & McKenna, 2010) and to illuminate broader trends. Then I present graphical timelines of coded statements for two teams (Rail 1 and Stat 1). These timelines show indicators of all coded statements for a given team in chronological order and thus provide a visual sense of the types of statements (defined by the codes) that the students were saying and when. Knowing *when* certain kinds of statements were made may be at least as informative as knowing *that* they were made. Section 1 concludes with interpretation of two teams' timelines and an overview of the insights gained from analysis of the code distributions within the student teams' online discussions.

PERCENTAGE OF WORDS CODED USING INITIAL SCHEME

Student Teams	Rail 1	Rail 2	Rail 3	Rail 4[11]	Stat 1	Stat 2
Coded Words	8151	4870	2492	3709	5494	5438
Total Words	9210	5623	2873	5679	6198	6055
% Coded	89%	87%	87%	65%	89%	90%

Table 4-1: Percentage of words coded from transcripts of online interactions

Table 4-1 lists for each of the six student teams for which I collected data the percentage of words coded for that team from their online discourse transcripts. I counted as a coded word any word in a statement that I assigned one or more codes. To clarify, though my analysis focuses on discourse at the statement level, I chose to count words because I labeled individual statements with multiple codes—thus, counting the percentage of statements coded does not constitute a meaningful representation of the percentage of the discussion language coded. The percentage of statements from the

[11] The percentage of words coded for Rail 4 is low in comparison to the percentages for other teams, because Rail 4 was the only team to have an extended discussion about programming and electronics. Since Rail 4 was the only team to do so, I decided not to include statements about programming; therefore many of these statements were not coded.

teams' online discussions (counted by words) is high, but this may be explained by the fact that the students were instructed to post once per class day to the online discussion and that each post must be substantive. Thus while the students' online discussions were informal, they were likely more focused than natural conversation.

Class periods 3 and 5 had six student teams: Rail 1, Rail 2, Rail 3, Stat 1, Stat 2, and Stat 3. These were the original six candidates for coding online discussions. For my analysis, I substituted Rail 4 (from period 2 and period 8 of the same Spring 2010 robotics class) for Stat 3, because Rail 4, unlike all the other teams in this study, had developed a complete set of drawings of exceptional quality. I believed that the discourse of the one team with viable, up-to-date drawings should be included when creating my coding scheme. I also wanted to know what effect such drawings had on Rail 4's discussion.

EXAMINATION OF CODE DISTRIBUTIONS

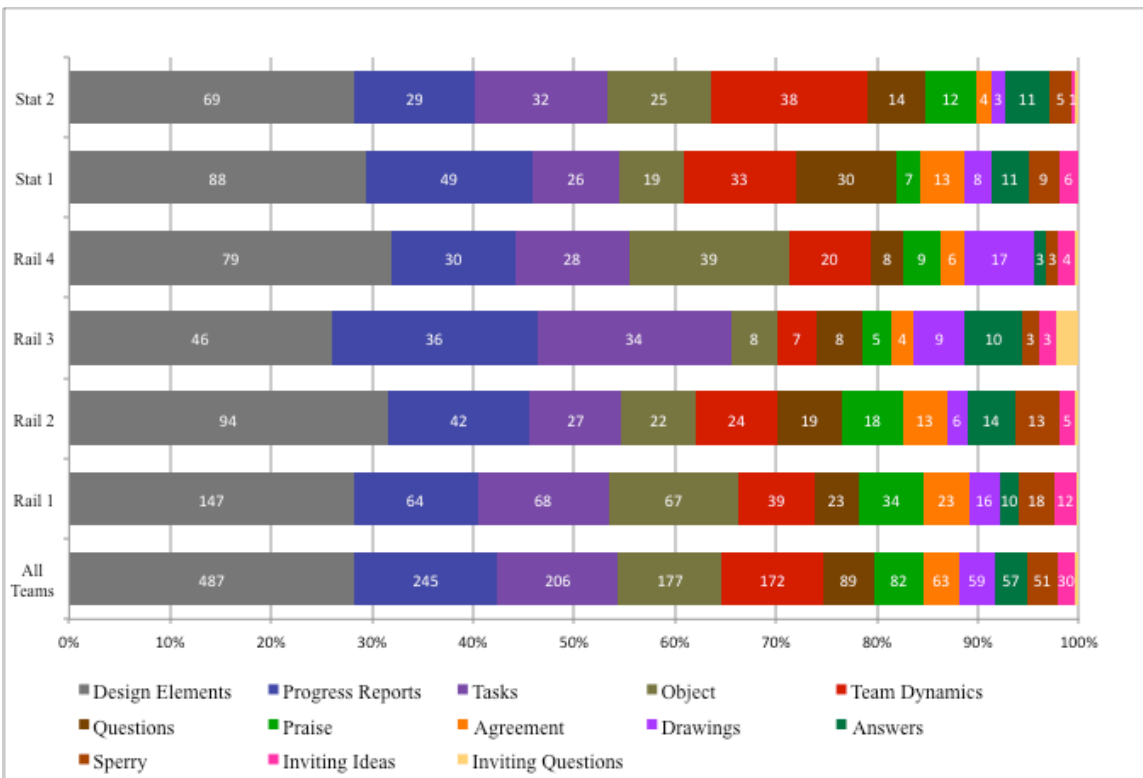

Chart 4-1: Distribution of coded statements in online transcripts for all six teams

Chart 4-1 shows for each of the six student teams the distribution of codes for the online discourse of each team and the aggregated distribution of codes for all six teams.[12] Each colored block is labeled with the number of times that statements with that code appeared in that team's discussion. The x-axis indicates for each code the percentage of that team's overall online discourse in which the code appeared. For example, team Stat 2 made 29 Progress Reports, which constituted about 12% of the coded statements in their online discussion. The All Teams bar sums up the counts and coded statements for all six teams. The colored blocks in the All Teams bar indicate a decrease in frequency of a coded statement running from left to right. Note that the names in the legend correspond to that order; hence, the colored blocks for each team occur in the order of the blocks in All Teams. The order of appearance from left to right does not strictly decrease for every team, but the decrease is a common trend.

In the aggregated data in the All Teams bar, Design Elements was the most frequently appearing code, at 28% of the total online discourse. Moreover, a combined total of 74% of the aggregated statements were made up of Design Elements (28%), Progress Reports (14%), Tasks (12%), Object (10%), and Team Dynamics (10%). Hence, in the students' online discussions, the majority of their discourse was focused on describing their ideas, tracking and attempting to make progress, and figuring out how to work together.

After Team Dynamics (at about 10% frequency), code frequencies drop to 5% or less. Compared to the frequency of Design Elements, Progress Reports, Tasks, Object, and Team Dynamics, there were relatively few instances of Questions, Praise, Agreement, Drawings, Answers, Sperry, Inviting Ideas, and Inviting Questions. The low occurrence of Inviting Ideas and near nonexistence of Inviting Questions (except for Rail 3) suggests that either the students expressed little interest in each other's ideas or that they expressed their interest in other ways. Also note that Praise, Drawings, and Sperry were also comparatively low, and I will address those more thoroughly later. The incidence of Agreement statements was also low—about 3% in the aggregated codes for

[12] I describe the codes in Chapter 3 and provide exemplar or representative statements for each code in Appendix F.

all six teams. It may be worth noting later what sorts of things the team members were agreeing on, and how they may have been expressing agreement in other ways, perhaps implicitly. For most teams (again, with the exception of Rail 3), and in the aggregate, the number of Questions well exceeds the number of Answers. Perhaps there were many unanswered questions. On the other hand, in my coding I counted every Question, even those questions that were asking the same thing. It could be the case that a single Answer addressed multiple Questions.

All told, there were relatively few occurrences of explicit statements (e.g., Answers) indicative of students attending to each other's ideas. Before making declarations about the students' attentiveness, however, I will investigate further to see if they were attending to one another's' questions and statements more implicitly.

For context, I return briefly to the coding scheme that Leema Berland and I devised in the pilot study (Berland & McKenna, 2010), in which Berland and I began coding the discourse of team Rail 1 (see Table 4-2). The Managerial and Design general topics we arrived at informed my dissertation study analysis.

General Topic	Specific Topic Code	Definition	Example
Managerial	Task Setting	Telling another group what to do and/or when to do it.	"…feel free to do what ever during your class that's doesn't involve the drive train"
	Progress Reports	Telling what a group did usually on a particular day.	"So, as you can see we built the prototype of the roof today…"
	Organization	Any comment related to necessary organization of support systems: tools, robot location in classroom, locations of files, etc.	"Also I disagree with building the roof first because it's the one part that all of us are really unsure about."
Design	Design Modification	Any proposed or enacted conceptual or physical change.	"So what about the metal basket instead of the funnel. Or would that still make it too big?... I think it may be a lot easier that funnel"
	Observation	Any comment in which the writer refers to a visual inspection of an artifact	"…and when the claw grips the ball it keeps on wanting to slip…"

Table 4-2: Pilot Study Code Categories

For the dissertation study, after my initial coding of the six teams' online discussions, I clustered the coded statements into four broad categories (see Table 4-3) so I could get a better overall idea of the content of the students' discussions. Of these four, the *Design* and *Management* categories were inspired by the 2010 pilot analysis study.

Category	Codes	Description
Design	Design Elements Drawings Object	Codes that are specifically associated with the physical design aspects of the challenge
Management	Tasks Progress Reports	Codes that relate directly to team tracking of work and progress, time management, delegation of work
Team Dynamics	Team Dynamics	Statements that address problems or voice concerns about issues of team collaboration. May include personal complaints and accusations.
Discourse Moves	Praise Sperry Agreement Questions Answers Inviting Ideas Inviting Questions	Discursive moves within the discussion.

Table 4-3: Dissertation Study Code Categories

The coding scheme I devised for this dissertation study differed from the pilot analysis coding scheme for several reasons, including that for the dissertation I, (1) analyzed the discourse of five additional student teams, and (2) embarked on a new examination of the discourse using pragma-dialectics theory rather than a more general theory of scientific argumentation. Two codes used in the pilot analysis remained the same in my dissertation analysis: *Task Setting* (shortened to *Tasks* for my dissertation) and *Progress Reports.* For the dissertation study, I dropped the pilot study's code for *Organization* because this code was not prevalent across the discourse of the six teams. *Design Modification* became *Design Elements* to broaden its scope to include not only proposed modifications, but comments on such modifications and on the overall design as well. As a category and code name, *Team Dynamics* was revealing because it includes statements in which a team member was expressing perceptions on communication, team relations, design process, etc. During the coding process, I discovered a rule of thumb that the presence of *Team Dynamics* codes suggested that things were not going well for that team. As I will expand upon later, examining the problems that a team was having provided important insight into the nature of their communication and argumentation. I arrived at the dissertation study's larger category of *Discourse Moves* (incorporating *Praise*, *Sperry*, *Agreement*, *Questions, Answers*, *Inviting Ideas*, and *Inviting Questions*) as a logical abstraction related to argumentation and the students' resolution of differences of opinion. The pilot study's *Observation* was changed to *Object* to include any reference to the object being engineered, including visual inspection, tactile inspection, references that weren't overtly visceral, and analogies made from existing objects as opposed to analogies based on mental images.

Despite these changes to the terminology for categories and codes, similar patterns emerged from my analysis of the discourse for all six teams (see Chart 4-2). As in the pilot study, the majority of the teams' discussions consisted of statements that were related either to *Design* or *Management*. This finding led me to suspect that most of the students' specific argumentation statements would sort into these categories. What the pilot study did not account for were statements that were neither design-specific nor managerial. These statements sorted into two new categories, *Team Dynamics* and *Discourse Moves*. Though analysis of the coding revealed these statements were fewer in number than those in the *Design* and *Management* categories, pragma-dialectical theory suggests these statements may have played important roles in the students' process of resolving their differences of opinion.

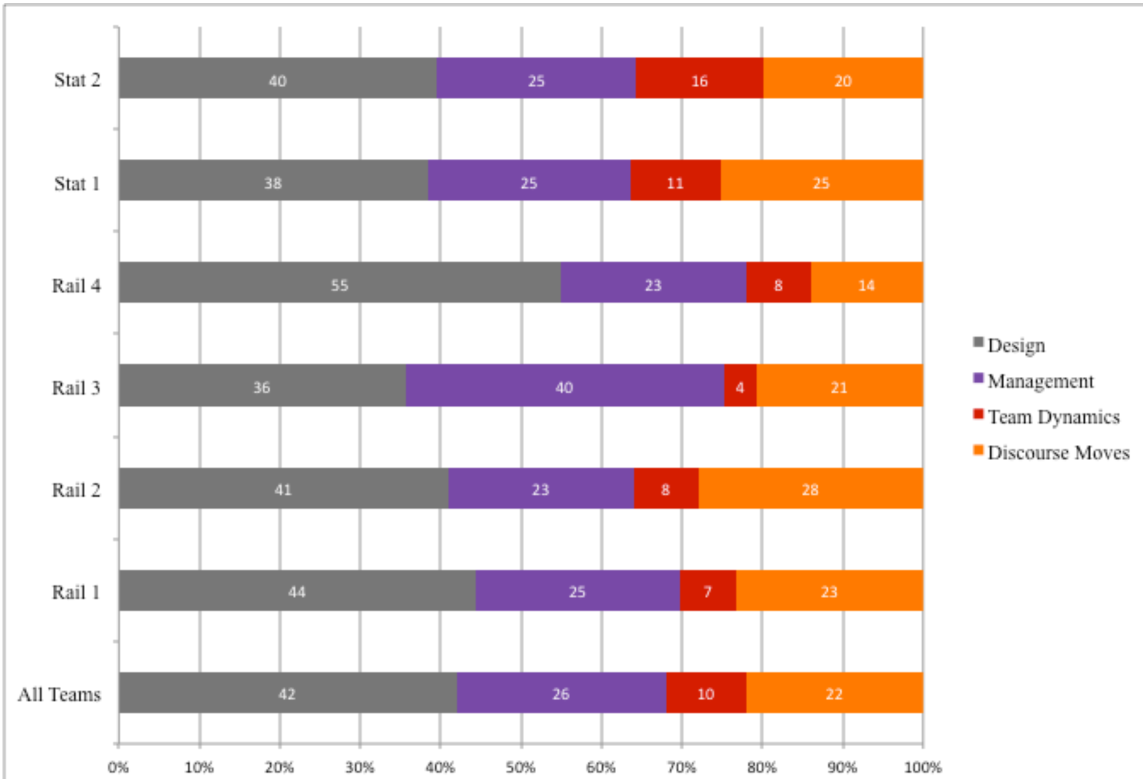

Chart 4-2: Distribution of code categories in online transcripts for all six teams

The dissertation coding analysis shows that for all six teams, the majority of the discussion (~70%) focused on issues related to design and management. It also reveals that around 30% of the teams' discussions contained other kinds of statements that could reveal important aspects of their design deliberations. The next step in my analysis was to sequence all the coded statements for two student teams[13] in timelines to assess whether additional patterns would emerge from their discourse.

Of course what can be ascertained by examining codes in isolation is limited, and later I will take a more qualitative look at the discussion statements themselves. However, patterns in the timeline may provide insight on what to look for in the online discourse text. The timelines may also provide evidence to support my interpretations of the teams' communications processes and internal dynamics.

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[13] I have created timelines of two teams, Rail 1 and Stat 1, because these are the teams for which I have accompanying classroom video.

TIMELINES OF TWO STUDENT TEAMS' DISCOURSE ABSTRACTED THROUGH THE CODES

The timeline sorts codes from the Dissertation Study Code Categories (Table 4-3) and for the various robot subsystems to reveal the sequence and density of various coded statements, as well as information about which types of codes occurred concurrently. Each team—Rail 1 (which worked on the robot that moved along the rail) and Stat 1 (which worked on the stationery robot) consisted of roughly ten students; each team of ten was spread across two class periods (third and fifth periods), and discussion between the class periods occurred online. Each timeline covers roughly 12 class days, which are indicated on the figure by pairs of white then gray vertical bars (one white then one gray indicates an entire day, one meeting of period 3 followed by one meeting of period 5).[14]

[14] In Chart 4-3 a gray vertical bar appears first because a member of period 5 posted to the online discussion before anyone from period 3 posted.

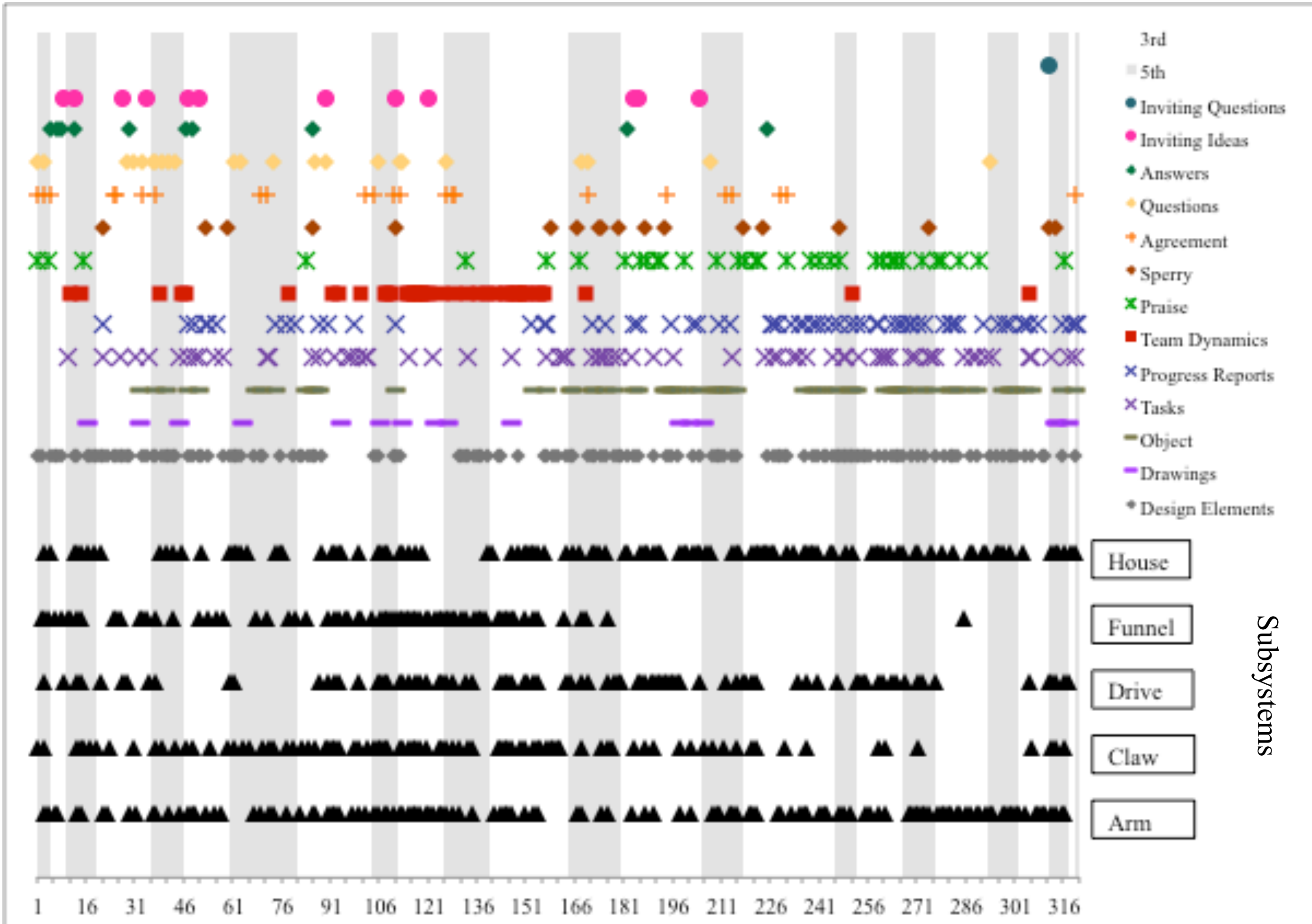

Chart 4-3: Timeline of Rail 1 Student Team Discussion and Robot Subsystem Codes

Chart 4-3 shows the timeline for all coded statements for the student team Rail 1. Each mark represents one coded statement. (Note that the timeline focuses on *codes* rather than the more abstract *categories* listed in Table 4-3.) Marks on white background indicate statements made by students in the third-period class; marks on gray background indicate statements from the fifth-period class. The thickness of each column indicates the number of statements coded during that class period. It happened that a student from fifth period posted online first; hence, the chart starts with a gray bar. Subsequently, third-period posts occurred before fifth-period posts, thus each white-then-gray column pair represents one class day. Black triangles show statements that refer to a particular robot subsystem (see Table 3-4). Design Elements codes (gray diamonds), Object codes (olive green lines), and Drawings codes (purple lines) together make up the *Design* category (Table 4-3).

Tasks codes (purple X's) and Progress Reports codes (blue X's) make up the *Management* category (Table 4-3). Team Dynamics codes (red squares) constitute the *Team Dynamics* category, and the remaining codes (Praise: green *'s; Sperry: brown diamonds; Agreement: orange +'s; Questions: yellow diamonds; Answers: green diamonds; Inviting Ideas: pink dots; and Inviting Questions: blue dots) make up the *Discourse Moves* category (Table 4-3).

Code marks other than subsystem codes (black triangles) can refer to any robot subsystem or can indicate statements of a general nature. Values for the x-axis correspond to the unique number assigned to each coded statement. Throughout Chapter 4 and the remainder of this study, I will label coded statements by (Day, Unique Number)—for example, (3, 31) refers to day 3, statement 31. According to Chart 4-3, for example, statement (3, 31) was made by third period since the x-axis value 31 is on a white background.

This timeline provides at least five insights into communication in the Rail 1 team.

(1): The black triangles (subsystem statements) show that the original four subsystems (Frame (more commonly referred to as House), Arm, Funnel, and Claw) identified in the third-period proposal (which predates the span covered in this timeline) expanded into five subsystems, which were mentioned multiple times nearly every class day by both the third- and fifth-period students. Considering each subsystem as an individual difference of opinion, Chart 4-3 suggests that Rail 1 attempted to resolve all subsystem-related differences of opinion simultaneously, as opposed to sequentially, which suggests that the differences of opinion were interrelated.

(2): Design Elements codes (grey diamonds) also appear with high frequency from the beginning to the end of the online discussion transcripts. Statements about Design Elements can refer to a specific robot subsystem or to the design as a whole. By definition, Design Elements codes represent the ideas or attributes of a physical object; statements coded Design Elements include descriptions, explanations, and suggestions for modifications of the object, and so on. Such statements are references to the design itself. The high frequency of Design Elements codes (the most frequently occurring code across all six teams) suggests that the students primarily focused on design concepts and made several design-related statements each class period. For Rail 1 (Chart 4-3), the frequency of Design Elements codes was high for both class periods (note the gray diamonds over both the white and the gray column backgrounds).

(3): Near line 166 of the transcript (as noted on the x-axis), there is a shift from Team Dynamics statements to Praise statements. This shift suggests that the team's interactions changed from problematic to more cooperative, because in the context of my study, Team Dynamics codes imply that things aren't going well for the team, whereas Praise codes indicate that the students like what they are seeing and are encouraging each other to keep it going. Such a sudden shift in their discourse may have been prompted by a significant event. Also, just before and after line 166 appear multiple Sperry codes, suggesting that the significant event may have been influenced by a timely intervention by the instructor. Also near 166, discussion of the Funnel subsystem stopped, suggesting that a resolution may have been reached. It turns out that the Funnel was never built; it only existed as an idea and a drawing. This fact was clear through classroom observation and video, but it is also the case that no Object codes in this discourse timeline referenced the Funnel specifically.

(4): Though Progress Reports codes occur throughout the discussion, they became much more dense near the end of the discussion and after the significant event. The increased frequency of Progress Report codes suggests that the students' design process became more productive. In fact, these codes occurred with similarly increased frequency from both the third and the fifth class periods, suggesting that both periods were contributing to the increased productivity. Moreover, Progress Report codes occurred in the relative absence of codes for Team Dynamics, which could imply satisfactory collaboration from both periods.

(5): With the increase of Progress Report and Tasks codes came an increase in Object codes for both class periods. Together, these co-occurrences imply that Rail 1 was making frequent managerial reports that focused on their Object. The timeline suggests that both class periods were equally engaged in this process. Also, this shift was happening concurrently with Praise statements, by which one might surmise the two class period teams were pleased with their productivity.

In summary, the timeline pattern of coded statements from Rail 1 suggests that this team engaged in a satisfactory (by their indication) resolution process. Team Dynamics was largely replaced by Praise, with a continued high number of Tasks and a concomitant increase in Progress Reports and Object references. Statements referring to the instructor had a significant showing around what appears to be a turning point, after which the instructor was mentioned several more times to the end. Also, the cessation of the Funnel discussion suggests that some resolution occurred mid-discussion. Of course these indicators don't demonstrate the particular quality of the students' statements, nor do the indicators provide details about the events that took place. To explain the nature of this team's deliberations more specifically, I will discuss particular statements from Rail 1 later in this chapter .

For Rail 1, the timeline was revealing. Most strikingly an important event seemed to take place on day 8, near line 166,[15] which was a turning point for the team. This is a good point of entry for further examination. Specifically, the Team Dynamics, Praise, Sperry, and Object coded statements are of particular interest,[16] as is the abrupt termination of discussion around the Funnel subsystem. The appearance pattern for each of these codes changed considerably around line 166. Note that three of these four codes (Team Dynamics, Praise, Sperry.) fall outside the more predominant (in terms of number of coded statements) Design and Management categories (Table 4-2). Although the Team Dynamics and Discourse Moves categories included fewer coded statements in the online transcripts, they seem to have played pivotal roles in Rail 1's discussions.

Admittedly, Rail 1 was the team with whom I was most familiar. (I was able to sit near them throughout the semester, and consequently, I have the best video data for them as well.) I could be reading in to their timeline more than it reveals on its own. As a comparison, then, I have also created a timeline for the team Stat 1. That team sat on the opposite side of the room from me and was frequently blocked from my view by tables and chairs. Direct access to them was limited, and consequently, I have less (and poorer quality) video for Stat 1. My analysis of the following timeline is thus less informed by my direct observations, so its analysis can serve as a good counterbalance to my analysis of Rail 1.

[15] Line 166 sits within the eighth pair of white-then-gray vertical bars. I dropped the labels Day 1,…, Day N to reduce the clutter on an already complicated chart.

[16] Progress Reports and Tasks also intensify after this turning point, but the frequency of both these codes was also fairly high before line 166.

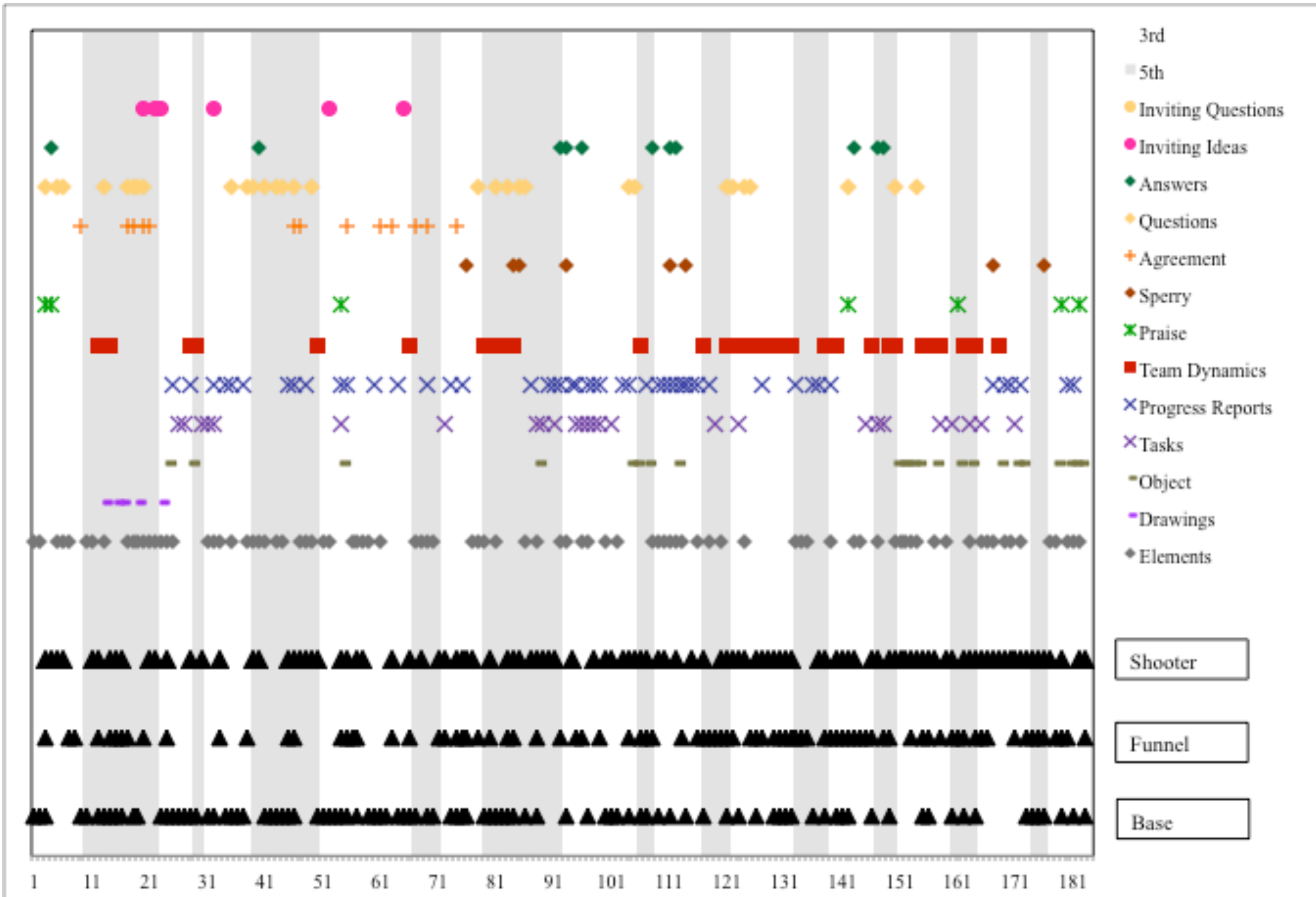

Chart 4-4: Timeline of Stat 1 Student Team Discussion and Robot Subsystem Codes

Chart 4-4 gives a timeline of coded statements for team Stat 1. The color and symbol schemes match those of Chart 4-3. The first impression I get is how few Discourse Moves codes (e.g., Praise: green *'s; Sperry: brown diamonds, Agreement: orange +'s; Questions: yellow diamonds; Answers: green diamonds; Inviting Ideas: pink circles;, and Inviting Questions: yellow dots) there are compared to the number of these codes in the Rail 1 timeline. And though both the Rail 1 and Stat 1 teams were large (10 members each), Stat 1 has far fewer coded statements. In fact, Stat 1's online discussion was 2,657 words shorter than that of Rail 1.

As did Rail 1, Stat 1 initially discussed all their subsystem disputes (Shooter, Funnel, Base) frequently; unlike Rail 1, Stat 1 continued talking about all three of their subsystems throughout the duration of their discussion. This constancy suggests that the Stat 1 students tried to resolve all their differences of opinion simultaneously. In fact, this attempt to resolve multiple differences at the same time was common to all six teams.

Another similarity between the discourse of Rail 1 and that of Stat 1 is that the Design Elements codes occur with high frequency throughout the entire discussion. Further, for Stat 1, the subsystem codes and Design Elements codes occurred with more or less equal frequency in both the third-period and the fifth-period classes, indicating the discussion was not unique to just one class period or the other.

The Discourse Moves codes, while fewer in number than for Rail 1, help tell the rest of the Stat 1 team's story, which differs from that of Rail 1 in three important ways.

(1): Team Dynamics codes occur across the entire Stat 1 discussion, and the frequency of Team Dynamics code occurrence increases near the end. This pattern suggests that teamwork-related problems got worse as the deadline approached. There are also very few Praise statements, and they are spread out across the 12 days of the timeline. Either explicit praise was not how this team communicated, or they were not happy with their design or each other. The higher frequency of Team Dynamics codes in comparison to such codes for Rail 1 suggests the latter. In fact, high rates of Team Dynamics statements, especially in the absence of Praise statements, can influence how the other codes occurring concurrently are interpreted. For example, Progress Reports, in the presence of Team Dynamics, may not have been considered less valuable than if delivered concurrently with Praise statements. In general, Team Dynamics codes indicate that things aren't going well, though naturally the codes alone can't convey the details of the problems the team was having.

(2): In the middle of Chart 4-4, there is a high density of Progress Reports that corresponds to a relative absence of Team Dynamics. In the middle of their discussion, Stat 1 may have been making progress. However, after line 121 (on the x-axis), Progress Reports codes decrease, Team Dynamics codes increase, and active discussion of all subsystems continues. Perhaps that progress wasn't worthwhile to the students.

(3): In the Stat 1 team discussion timeline, Object codes are sparse in comparison to those for Rail 1, and Drawings codes are even fewer and appear only at the beginning. This pattern suggests that Stat 1 did not use their drawings as a supportive tool and that they had difficulty creating a object worth referencing. The highest density of Object codes occurred at the end of the Stat 1 timeline, suggesting that they may have scrambled to get something built in the last three days.

As with the Rail 1 timeline codes, Team Dynamics, Praise, and Object are three of the most telling codes in Stat 1's timeline. Judging from the two timelines, it appears that the quality of the teams' communications, with problems therein indicated by Team Dynamics codes, had a major influence on their overall effectiveness. I also observed in both timelines that more—and more frequent—Object codes may indicate an emerging solution to the teams' collaboration issues.

REVIEW OF SECTION 1: DESCRIPTIVE ANALYSIS

The code distributions from the dissertation study align with those of the pilot analysis; that is, codes falling into the Design and Management categories were the most common for all six teams. Less common were codes grouped as Team Dynamics and Discourse Moves. But less common does not necessarily mean less important with regards to argumentation. Coded statements that fall outside the two main categories (Design and Management) may prove analytically revealing and important to a team's resolution process.

The code timelines revealed common trends. Both teams analyzed in section one discussed all of their robot subsystems simultaneously. In fact, as rail 4's timeline (later in this chapter) and preliminary timelines for teams not presented here, discussing all subsystems simultaneously appears to be a class-wide trend. (The quantity of Design category statements from Chart 4-2 suggests this is certainly possible.) My methodology did not include asking students direct questions about their design discussion, but I can speculate as to why this occurred. Designers (most notably professionals) commonly allow aspects of their designs to remain ambiguous for the time-being, tabling related discussions to be taken up at again later (Cross, Christiaans, & Dorst, 1996; Minneman, 1991). They do this for a number of reasons including expediency (i.e. not getting bogged down by too many details) and a desire to focus attention on particular design aspects (subsystems, for example) they deem more immediately important. The ability to leave design aspects ambiguous and postpone related discussion, I believe, lies within a sense of self-efficacy—the belief that the designer will be able to figure it out when the time comes. Perhaps this ability come through experience. Novices, on the other hand, may not have such self-efficacy; they may be unsure that they will be able to figure it out when the time comes. If this is the case, then it’s no surprise that a team of design novices would want to discuss all subsystems simultaneously because they don’t know what they will or wont’ be able to produce later on.

The timelines also suggest that statements coded as Team Dynamics (TD) may play an important role in providing analytical insight into the student teams’ differences of opinion. The two examples are a) Rail 1’s timeline showed a high density of TD codes near the middle of their discussion and few thereafter; b) Stat 1’s showed some TD codes near the beginning of their discussion and then a plethora near the end. Perhaps resolutions are preceded by a density of TD codes. Whatever the case, the timelines suggest that TD coded statements are worth further examination, and I do so in section 3 of this chapter.

BRIEF REFLECTIONS ON THE CODING SCHEME

Coding the teams’ online discussions the way I did had strengths and shortcomings. Tracking the discussion by subsystem proved worthwhile. It revealed how all of the teams basically tried to design all of their robot’s subsystems simultaneously. It also showed when certain subsystem discussions began or ended, namely, the Funnel subsystem in Rail 1. Coding Progress Reports and Tasks was revealing in the sense that the teams made such statements frequently, which showed the teams' interest in reporting progress and making new progress. However, these two could were somewhat misleading, because in the case of Stat 1, a Progress Report from one class period was not necessarily perceived as progress by the other class period. In the same sense, a Task assigned by one period was not necessarily recognized as valuable by the other.

Team Dynamics codes were revealing, at least in the sense that they helped to guide my analysis and provided some insight into how a team was getting along. Attending to a team's internal issues seems worthwhile and may reveal much about the team members' thinking. In further studies I recommend coding for Team Dynamics with greater refinement and specificity. In the same sense, coding for Praise may also continue to prove insightful.

Other Discourse Move codes like Inviting Questions and Inviting Ideas were rare, and they didn't provide me much insight.

All told, the primary shortcoming of this coding scheme, besides the inherent subjectivity of a solitary analyst, was the fact that the codes themselves were not directly tied to the argumentation structure. A coded statement could have argumentative meaning well beyond its descriptive code. In other words, some code pattern may *suggest* that resolution may be taking place, but it's by no means conclusive. One possible exception to this is Team Dynamics. It did appear that an abundance of TD codes strongly suggested that resolution is *not* occurring.

The overall goal of the coding scheme was to determine a short list of the kinds of statements that student make during design deliberations—a list that would at least make sense and possibly be useful to an engineering design teacher. There is a short list, and it contains thirteen kinds of statements. How useful a teacher (or researcher) will find that list remains to be seen.

Section 2: Pragma-dialectic Analysis

In this section I take a closer look at actual statements from the online discussions of two student teams. This is an attempt to determine if and how argumentation emerged in the Pragma-dialectic sense. In this section, I present and interpret many student statements extracted directly from the online discussions. My intention is to provide the reader with a sense of how the students' arguments developed, and how those arguments fit within the Pragma-dialectic framework.

PRAGMA-DIALECTICS STAGE ANALYSES OF RAIL 1 FUNNEL DISPUTE AND STAT 1 SHOOTER AND BASE DISPUTE

While the timeline coding frequencies revealed patterns that can lead to insight, the coding analysis does not directly address the qualitative aspect of the students' argumentation. For that analysis, I use the pragma-dialectics theory descriptions of the four stages of a critical discussion to determine which of the students' statements belong to which stage. Specifically, I walk through a PD stage analysis for one subsystem discussion by Rail 1 and the primary difference of opinion for Stat 1. This PD analysis is an effort to characterize the flow of these two teams' resolution processes around particular design subsystems by first viewing that resolution process linguistically and then reconciling that linguistic process with the physical design developments taking place in team's overall design process.

Rail 1 Funnel Dispute

The four stages of a critical discussion as outlined in PD do in fact enable analysis of how Rail 1 resolved a single dispute regarding the Funnel aspect of their robot engineering challenge. This PD analysis will clarify how specific statements contributed to (or detracted from) the students' resolution process. I will provide a PD analysis of the Funnel dispute, and then a shorter analysis of the Stat 1 shooter and base dispute. These analyses were originally intended to serve as an existence proof for using the four stages of PD argumentation to help students (specifically, novice engineering design students) accelerate their learning and design resolution processes. In fact, the analysis led to an alternate conclusion—that although the students engaged in argumentation, that process not only did not accelerate their arrival at design solutions, but may in fact have slowed their progress.

Overview of the Rail 1 Funnel Dispute

The difference of opinion around the Funnel consists of whether to use it and, if so, how it should be configured. The original intention behind the subsystem was expressed in the third-period group's design proposal (see Appendix D1). That is, the Funnel would serve as a device to collect and hold balls so that several could be deposited one at a time into the nearby stationary robot on the floor. In this design proposal, the third-period subset of the Rail 1 team asserted that the Funnel would save time during the competition. In the online discussion, the roles of *protagonist* and *antagonist*, that is, of those speaking for or against the Funnel, emerged with third period as protagonist and fifth period as antagonist.

Members of the Rail 1 team proposed three possible configurations to serve the function of holding balls prior to depositing them. The idea began as a Funnel in third period's design proposal. Later, a new configuration was offered by third period in the form of a rectangular box, called the Basket.[17] It was also suggested that the idea of storing balls be abandoned in favor of selecting and dropping one ball at a time. Last, an idea for using a metal support bar was suggested to help in the process of selecting and dropping one ball at a time. By day 8, all discussion of the Funnel and related configurations abruptly ceased.

Each possible configuration could be labeled as its own difference of opinion and be described through each of the four stages. However, because all ideas related to the Funnel were in float with no individual resolution, I have considered the Funnel subsystem as a single difference of opinion with multiple contributing premises.

[17] Basket is considered part of the Funnel subsystem because it is a design modification that was meant to serve the same purpose as the Funnel.

PD Stage	Description
1. Confrontation	Doubt is cast upon a standpoint; thereby establishing a difference of opinion.
2. Opening	Parties to the difference of opinion seek relevant common ground (background knowledge, discussion format). Parties determine if their “zone of agreement” is sufficiently broad to conduct a fruitful discussion. Parties establish themselves as for or against the standpoint (van Eemeren, 2004, p.60).
3. Argumentation	Arguments for the standpoint are advanced and critically evaluated by those casting doubt upon the standpoint.
4. Concluding	Resolution: The standpoint is accepted when doubt is withdrawn, or the standpoint is withdrawn due to overwhelming doubt about it.

Table 4-4: The pragma-dialectical four stages of a resolution of a difference of opinion

1. Rail 1 Pragma-Dialectics Confrontation Stage

The confrontation was established with two statements, (1, 3) and (5, 79).[18] One thing to note immediately is that the statements take place on day 1 and day 5. Pragma-dialectics theory does not assume that indicators occur in PD stage order. In fact, the *transformation of permutation* (van Eemeren & Houtlosser, 2006) is used to reorder statements from discourse in order to clarify and better understand the resolution process. However, I have preserved time information (the day in which the statement occurred) in order to demonstrate how the students’ deliberations evolved over the course of several days.

Direct quotes from the students’ online discussions are indented and labeled thus:

(day, unique number) (Assigned Discourse Codes) (class period—3rd or 5th).

I redacted any full names used in the online discourse; other than that, the student statements remain unchanged from the original.

> (1, 3) (Questions, Agreement) (5th): The only concerns that i have is the funnel. I like the idea but i'm not sure how the arm will get the balls to the funnel and we also need to figure out where to mount the funnel so that it's not in the way.

[18] The transcripts of the students’ online discussions are coded by the day of the 12-day robotics challenge and the unique number assigned to the statement, hence (1, 3) means day 1, statement unique number 3.

> (5, 79) (Design Elements) (5th): I'm starting to have doubts about the funnel. Although I think that a funnel would be a good thing to have, but I fear that the funnel might make the robot too big. But if I have to choose between a funnel made out of Lexan[19] and the metal holder, I'd choose Lexan because it will be easier to bend and adjust.

In the two statements, Rail 1 fifth period expressed doubt regarding the use of the Funnel, thereby establishing a difference of opinion. This is an explicit difference of opinion, since fifth period used the specific terms "concerns" and "doubts." These expressions of doubt not only question the best way to construct the Funnel, but also whether the Funnel should exist at all. The difference of opinion the team has to resolve is twofold: whether to use the Funnel (or a similar configuration), and if so, what the best building material would be.

2. Rail 1 PD Opening Stage

Seven statements about the Funnel fall into the PD Opening Stage. These statements indicate premises and new ideas put forth to help resolve the dispute. The statements also serve as invitations for any and all team members to contribute to the resolution process.

> (2, 7) (Answers, Design Elements) (3rd): Yeah the funnel and arm will need some tinkering but in general the funnel is going to lean away from the ball mount so it doesn't run into anything.
>
> (2, 9) (Inviting Ideas) (3rd): maybe we'll make a video :) Does anybody have any ideas of how we can shut off the bottom of the funnel to hold in the balls until dropoff?
>
> (3, 34) (Inviting Ideas) (3rd): Also, if we didn't use a funnel are they're anyother ideas about how to collect multiple balls instead of dropping off a single ball each time?
>
> (5, 51) (Design Elements) (3rd): Instead of doing a funnel why cant we just have the robot pick up a ball and it goes to the place where the stationary robot is and drops it? Wouldn't it be easier? or have a metal holder that tips over and drops the balls into the stationary robot, instead of a funnel? have the metal holder tilted up

[19] Lexan is a trademark term for a type of plastic (https://www.sabic-ip.com/gep/Plastics/en/ProductsAndServices/ProductLine/lexan.html). In class the students were using 1/4" sheets. Lexan became a classroom term referring to hard, translucent plastic sheets.

so that the balls don't fall out and then go to where the stationary is and tips over, dropping the balls into it. The metal holder could be thin so the balls are in a straight line and come out one at a time. there could also be a door/lid at the end so that we came control how many balls go in...?

(5, 54) (Design Elements) (5th): What we need to do is figure out a new funnel. We need to decide what we are going to use, how we are going to make it and get balls to it and how to release balls once they are in there

(6, 81) (Design Elements) (3rd): So what about the metal basket instead of the funnel. or would that still make it too big? i think that the basket-like thing would be a good idea. i don't know how we would put it together... i would like to have a few suggestions about it, and if you think that it's a good idea. i think it may be a lot easier that funnel and the funnel would be too big. but the basket-thing may be a little big also but not quite as big as the funnel.

(8, 143) (Design Elements) (3rd): i think that instead of having a basket, on the part of the claw, we have something like a flat metal bar under so that if the claw doesn't hold the ball well enough, it won't fall completely.

Statement (2, 7) offers a brief explanation of how the Funnel will work, and demonstrates by the need for “tinkering” that the design is incomplete; furthermore, statement (2, 9) invites ideas on how to complete the design. Although the explanation in (2, 7) could be considered a form of argumentation, and hence part of the Argumentation stage, I consider both statements part of the opening stage. First, by offering some explanation and inviting ideas, both statements seem to be attempts to promote buy-in from fifth period towards a resolution in favor of using the funnel. This is a common function of opening premises. Second, the stated need for tinkering suggests a tactic for finding the information necessary to successfully engage in the resolution process, and that all members were invited to participate.

Statement (3, 34) invites ideas for alternatives to the Funnel. Within the context of the students’ process, this statement amounts to inviting more opening premises. New ideas followed: statements (5, 51), (6, 81), and (8, 143) are three opening premises in the form of new design ideas for the Funnel. Again, while the statements include explanations, they do not seem specific enough to build from. Rather, they seem to serve as a way to sell the idea, rather than argue for its assembly and inclusion. Two Design Elements statements include indications of uncertainty and invitations for the other members to buy in to the idea enough to develop it, e.g. (6, 81) “I don’t know how we would put it together” and (5, 51), “Wouldn’t it be easier?”

The Opening Stage reveals three distinct ideas in play, each of which requires further exploration, or “tinkering,” in order to be assembled. All the above statements (except 5, 54) were made by third period, which is consistent with their position as protagonist that the original function of the Funnel—to store balls for deposit—should be addressed. Fifth period’s statement (5, 54) characterized the specific nature of this particular difference of opinion. It was the closest Rail 1 came to declaring the nature of the Funnel difference of opinion in a single statement. It addresses their dilemma regarding how the Funnel subsystem will function and how it should be built.

3. Rail 1 PD Argumentation Stage

The essential argument of fifth period, the antagonist, is that any Funnel configuration would take up too much space and unnecessarily overcomplicate the process.

> (5, 69) (Agreement, Design Elements) (5th): Funnel wise i'm gonna agree with K. i think the funnel attachment is gonna get to big and will over complicate the process. Remember Keep It Simple
>
> (6,104) (Agreement, Design Elements) (5th): So i think that the funnel is going to get in the way. It's not a weight issue, it's a space issue. I don't really get how the arm/claw will get the ball into the basket. I do like K’s idea of the basket better than the funnel. Also we have to work on where the basket is positioned and where the stationary robots are positioned to figure out if the basket is going to work.
>
> (6, 110) (Agreement, Design Elements) (5th): So, I guess the funnel wouldn't work because it would be way too big and we don't have enough space. I do agree that the metal basket is a good idea, but I am still worried about our limited space. I think we will brainstorm about the basket today, and don't plan on building anything this time because of the time constraint.
>
> (7, 130) (Design Elements) (5th): Edit @2:50 : so it seems like my group doesn't think the basket will work. I still really think that the basket would be a great function to have though, even if it will only be able to hold just one ball
>
> (7,132) (Praise, Design Elements) (5th): We like your idea a lot, but the only thing is that our group seems to think that the funnel won't work because there won't be enough room on the robot.

> (7, 136) (Team Dynamics, Design Elements) (5th): I also don't think the basket is going to work (b/c it will get in the way) but no one has addressed that either. I know that i went back and re-read all of yalls posts and i would appreciate it if yall did the same for us.
>
> (7, 139) (Team Dynamics, Design Elements) (5th): There really isn't room for a funnel or a basket, and our group has contributed ideas, but we really never got any feedback, which is super frustrating since we fell like we can't do anything.

Although the argument about the funnel taking up too much space is mechanically specific, it consists of declarations that the fifth-period students believe to be true. Their claims about size lack detail and provide no means of verification. Also, fifth period mentioned more than once that they still liked the idea of a Funnel. Hence, their argument is less about concept and more about utility. A likeable idea was no good if they did not know how to make it work.

Third period used two strategies to argue for the Funnel: *declaration of valu*e and *delegation of task*. Similarly to fifth period’s statements against the Funnel, third period’s statements lack detail.

Declaration of value:

> (6, 84) (Design Elements) (3rd): Also, even though the funnel might weigh down the robot but i think it is better to add it then to take it out.
>
> (8, 163) (Tasks, Design Elements) (3rd): I also really encourage reconsidering the basket. The robot has a high chance of dropping the ball if it has to hold it the whole time it is running down the rail to drop it in the stationary robot. Also, dropping each ball individually takes a LOT of time

While various persuasion strategies are common among designers (Brereton, Cannon, Mabogunje, & Leifer, 1996; Cross, Christiaans, & Dorst, 1996), third period, in using a persuasive strategy of arguing for the Funnel by delegating its design to fifth period, more antagonized than convinced fifth period to adopt the Funnel. Third period offered the job to fifth period, but didn’t offer further instructions and made no attempts to counter fifth period’s arguments about space and complexity.

Delegation of task:

> (3, 26) (Tasks, Design Elements) (3rd): If you guys want to make a funnel that's cool. It may be difficult though because we won't have a frame to build off of yet, nor material to build the funnel out of.
>
> (6, 96) (Tasks) (3rd): If you guys could draw up a complete idea for the funnel/ basket thing that would be superb! Maybe you guys could focus on that aspect of the robot?
>
> (7, 115) (Tasks, Team Dynamics) (3rd): Our thoughts were that since going back and forth with the arm and claw was getting frustrating and counterproductive, we would let you guys make the funnel/ basket. Let's just call it a basket.

Rail 1's argumentation stage in the Funnel dispute was marked by argumentation statements made at cross purposes. Whereas fifth period was arguing against the Funnel based on mechanical concerns, third period was arguing for it based on desirable functions that it would provide. The proposed function of the Funnel was never in dispute; both periods agreed to that: e.g. (7, 132). Argumentation regarding the Funnel was adduced by both periods (as protagonist and antagonist), but neither side was completely convinced by the other. The textual evidence suggests that they were not able to convince each other because they lacked a common point of reference. From the discourse analysis, it is clear that students in each class period had different ideas, and possibly different mental images (or object worlds), for the Funnel. Recall that Figure 4-1, below, from third period's design proposal, was thus far the only available representation of the funnel. I hypothesize that without a better, possibly physical, representation of the object, the protagonist (third period) and antagonist (fifth) couldn't fully grasp each other's arguments.

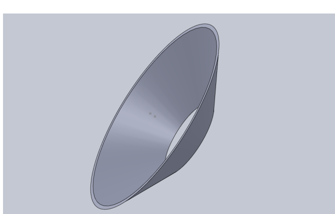

Figure 4-1: Image of the funnel proposed by Rail 1, third period.

4. Rail 1 PD Concluding Stage

The difference of opinion around the Funnel seemed to be resolved implicitly. Discussion of the Funnel essentially stopped on day 8, and no Funnel in any configuration was created.[20] Yet there were no statements in online discussion from either class period expressing that they had agreed not to use it. As the Arm and House subsystems became assembled, third period may have realized that there was no room for a funnel, or that its addition would have made the robot too complicated. Although fifth period seemed to realize this early on, their arguments against the Funnel were not convincing. My conjecture is that the resolution occurred after a final "convincing argument" that came in the form of the other two subsystems, which by day 8 were sufficiently assembled to provide a usefully comprehensive representation of the robot. At that point, it seems, both class periods were able to agree that the Funnel would not be feasible in any configuration.

Rail 1 PD Stage Analysis Summary

Uncovering the four PD stages within the Funnel discussion suggests that a resolution of the difference of opinion occurred but not purely as a result of their discussion about the Funnel. Rather, the implied resolution (by the sudden disappearance of references to the Funnel) in the text seemed to reflect another process relating more to the progress of the students' design into a physical manifestation, or object.

Stat 1 Shooter and Base Dispute

Now I will analyze the online transcripts for the Stat 1 team to follow the four pragma-dialectic stages as they emerged in a different sort of dispute. While the Rail 1 team was trying to decide whether to adopt or reject a single idea (the Funnel), Stat 1 was trying to decide between two competing ideas. As the two ideas were fundamental design plans, resolving this difference of opinion was critical to the team's success.

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[20] There is one last mention of the Funnel near line 286. No one responded to this statement, and no further action was taken regarding the Funnel. As this statement is a solitary outlier, I did not consider it as part of the Funnel argument.

Overview of the Stat 1 Shooter and Base Dispute

The Stat 1 discussion code timeline in Chart 4-4 shows three subsystem disputes for that team: Shooter, Funnel, and Base. I will analyze the stages of the Stat 1 team's critical discussion around the Shooter and Base because these were competing ideas. Stat 1 had a difference of opinion about whether to build their robot with a rotating base with one shooter (Base) or with a fixed base with twin shooters pointing in opposite directions (Shooter). Without context, these two design ideas can be difficult to envision at a useful level of detail, and so it was for the students, which is perhaps illustrative of the difficulties that these novice designers experienced as they attempted to envision two very different designs with sufficient clarity to discuss and develop either one.

Stat 1 had to make a decision as to which of the two designs they would pursue because the two designs were incompatible. They had to select one because both proposed designs were complex enough to require meaningful contributions from members of both class periods. Unfortunately, gauging from the online transcripts, neither class period possessed a particularly strong understanding of either design. They debated about perceived pros and cons of both designs without (apparently) possessing the tacit understanding necessary to build the mechanical systems essential for operation.

1. Stat 1 Pragma-Dialectics Confrontation Stage

> (1, 7) (Design Elements) (3rd): I am concerned that the it will be really complicated to operate a ball sorting device with the sensors and might require to many materials
>
> (1, 10) (Design Elements) (5th): However, i feel that with a rotating base the robot can easily become misaligned.

These two statements indicate that a confrontation exists and that there are doubts cast against both the rotating base (1, 10) and the twin shooter (1, 7). Both statements offer explanations for the concerns, which relate to potential problems with execution.

2. Stat 1 PD Opening Stage

I will list the voluminous Opening Stage statements first, and explain them at the end of the section.

(1, 1) (Design Elements) (3rd): i think that our group should start building the base because our base design enables the robot to rotate and aim left and right.

(1, 7) (Design Elements) (3rd): but if y'all can make it work then go for it.

(1, 9) (Agreement) (5th): Anyways, i hope that i have cleared up the problems, and i would agree with building the base first in order to have something to build on for both groups.

(1, 11) (Team Dynamics, Design Elements) (5th): About the rotation problems, in our design we had no plans to have the shooter rotate; in fact, our plans were to have two identical launchers aimed at either goals in order to avoid having to rotate and possibly become misaligned.

(1, 12) (Team Dynamics, Design Elements) (5th): I think that we should start by comparing designs. So that way we can see how each other thinks to start on the road of compatibility. If you submit your design proposal we can start to build.

(1, 13) (Questions, Drawings, Design Elements) (5th): How will the base of the robot rotate? Currently I just see that there are 3 wheels all facing in the same direction with no motors powering it and don't understand how it is supposed to function.

(1, 14) (Team Dynamics) (5th): First I think that both groups need to agree on one design before we can start building the robot. Possibly list out the pros and cons of each design, distinguishing which robot is more reliable/stable.

(1, 16) (Drawings) (5th): If you have trouble with solidworks like we do, feel free to just explain it in detail on a word doc or something like that.

(1, 18) (Questions, Agreement, Design Elements) (5th): I think that it rotating in a tank like way is a good idea, i just don't understand what you plan on it looking like

(3, 22) (Inviting Ideas, Design Elements) (3rd): i also feel like a rotating base will be less complicated than synchronizing the motors and sensors required to sense the type of ball and direct it to which ever shooter. but maybe you have a way in mind that isnt[this complicated]. my other concern about the two shooters is it may be harder to make small accuracy adjustments

(4, 40) (Answers, Design Elements) (5th): Regarding the double launcher, yes we will have to do some fine tuning before this design will work; but, once we have this set up perfectly (assuming that the distances won't change and the stationary robot is supposed to be in the same place every time) we will just need to change the programing to direct the ball to the right goal.

(4, 41) (Questions, Design Elements) (5th): Ok I like what i'm hearing for how it rotates, that makes a lot more sense. But have you considered how the axle might create too much resistance when it's rubbing up against the platform? If not, using a buffer of some sort might help

(6, 50) (Team Dynamics) (3rd): we should make a choice about the rotating base versus twin shooter.

(6, 53) (Team Dynamics) (3rd): once we do i feel that moving on will be a lot quicker process because we can get the base done and working and finish with time to do trouble shooting. [serves as an assurance]

(6, 66) (Team Dynamics) (5th): Ok yea we need to decide on one design

(6, 67) (Agreement, Design Elements, Inviting Ideas) (5th): I believe that the rotating base won't work during autonomus mode because it will be off by a couple of degrees after a couple of spins due to imperfections in the motors and there is no way to scan the balls. If you can propose some possible solutions to those problems and the ones i asked last time, i'd be ok with using that plan

(7, 79) (Team Dynamics, Design Elements) (5th): Also we still haven't really decided on the base. I would prefer it being stationary. This is because I'm still not exactly sure how a rotating one would work and think it would be much harder to build with no real benefits

(7, 80) (Team Dynamics) (5th): We all need to agree on this before we can move forward

(7, 82) (Team Dynamics) (5th): We would like for you to answer all the questions we had regarding the possible problems with the base, thank you.

The Opening Stage lasted seven class days, around half of their allotted time. From day 1 to day 7, there were six distinct statements calling for an open comparison of ideas to promote a resolution (1, 12), (1, 14) (6, 50), (6, 66), (7, 79), (7, 80). Because these statements were essentially repeated for seven days, they appear to have gone undigested and unheeded. There are also opening premises for both ideas—rotating base and fixed shooters—that sought to promote broad agreement but omitted details. These opening premises included ideas for ways to get started (1, 1), (1, 9), asking questions (1, 13), (4, 41), making assurances, (4, 40), (6, 53), and reiterating doubts (1, 13), (3, 22), (6, 67). These Opening Stage statements also included several expressions of a lack of understanding or an incomplete mental visualization of either design idea.

(1, 13)—"I just see that…i don't understand how it…"

(1, 18)—“rotating in a tank like way… i just don't understand what you plan on it looking like”

(3, 22)—“but maybe you have a way in mind”

Having a clear mental visualization of their design ideas was important to the students, and they were trying to develop those visualizations through their communication. This makes sense because the Opening Stage is a time to clarify the issues that need to be resolved. However, by the last statement in this stage (7, 82), fifth period was still chasing down unanswered questions.

3. Stat 1 PD Argumentation Stage

Argumentation Stage began on day 1 as well. This concurrent occurrence of PD stages may seem odd, but PD analysis includes the ability to reorder statements to clarify the resolution process (van Eemeren, 2006). While I did not reorder student statements, choosing to preserve the original sequence instead, the fact that both Opening Stage and Argumentation Stage statements appear as early as day 1 suggests that the students' argumentation patterns are not tidy or well-ordered (as is true for most natural human discourse). Also, many of the Argumentation Stage statements read like Opening Stage statements. As it is difficult to always provide an uncontestable demarcation between these two stages, for the purposes of my analysis, the Argumentation Stage statements must have greater specificity than the Opening Stage statements. This greater specificity can be evidenced through language with more descriptive detail or that is framed as more directly actionable than are the Opening Stage statements. For continuity with the Rail 1 analysis, I have also included *delegation* as a form of argumentation by persuasion.

(1, 13) (Design Elements) (5th): I suggest that if you still want it to rotate that it should have 4 wheels instead of three so that the rotation would be simpler.

(3, 26) (Tasks) (3rd): The top base will have to be fashioned in 5th period, and this assignment will be assigned to you.

(3, 27) (Tasks) (3rd): If you guys could work on making the base rotate, then that would be cool.

(6, 56) (Design Elements) (3rd): one thing i'm still concerned with is that the way the rotating base is going to work is that it will be powered by one motor in the

> center which is attached to the already built lower base and will turn the sheet metal base which will have everything else mounted on top such as the shooter and funnel but i am concerned that one motor turning this all might not have enough power.
>
> (6, 57) (Design Elements) (3rd): i think it's important that we try to make everything that's not the base, such as the shooter and funnel, as light as possible in order to make it easier for the motor to be able to rotate all of this.
>
> (6, 67) (Agreement, Design Elements) (5th): I believe that the rotating base won't work during autonomus mode because it will be off by a couple of degrees after a couple of spins due to imperfections in the motors and there is no way to scan the balls. If you can propose some possible solutions to those problems and the ones i asked last time, i'd be ok with using that plan.

Note that I include (6, 67) in both the Opening Stage and the Argumentation Stage. I did this because the statement served two purposes: 1) it asserts a claim that the rotating base won't work and provides detail explaining why that is the case, thus putting it in the Argumentation Stage; 2) it also solicits possible solutions to the dilemma, which puts it in the Opening Stage. Statement (6, 67) serves as an example of how difficult it is to rigorously demark one stage from another in the context of natural discourse. Clear demarcations, fortunately, aren't strictly necessary in pragma-dialectical analysis, as PD asserts that the stages emerge out of the resolution process as markers by which to describe that process. They are not meant to proceed in a lock-step sequence.

4. Stat 1 PD Concluding Stage

> (11, 127) (Progress Reports) (3rd): weve decided to go with one shooter and no sorter.

Stat 1 PD Stage Analysis Summary

This Stat 1 PD stage analysis shows two class periods talking across one another. Each period was promoting their own idea while criticizing the other. The discourse analysis reveals no animosity between the groups, even though frustrations grew high. They were not oppositional for the sake of adversity. Rather, neither class period seemed to understand or hold a sufficiently comprehensive mental image of either of the two design ideas—rotating base or fixed shooters—well enough to argue toward a constructive resolution. In fact, my impression from their discussions is that neither period understood either idea very well—not even their own. The Stat 1 team members made some descriptive statements. They also gave reasons for their ideas, but none of their arguments seemed convincing.

The Stat 1 team members overall were attending to each other's ideas, but without sufficient understanding, they tended to just keep working on the idea from their own class period.

> (9, 107) (Progress Reports, Object) (5th): We haven't seen anything extra being built. Because of this we are just going to continue building our design.

This unfortunate pattern explains the plethora of Progress Report statements in the middle of the Stat 1 discussion code timeline, followed by many Team Dynamics codes. Each class period was reporting progress, but to separate ends, about which they ultimately communicated their confusion and dissatisfaction.

Another way to recognize the disparity among team Stat 1 is that the Opening Stage contained twice as many statements as did the Argumentation stage. A relatively high number of Opening Stage statements suggests that the students were spending a lot of discussion time looking for relevant common ground (Table 4-3) upon which to build consensus around a single robot design. In an argumentative sense, the students struggled to find even one thing they all could agree upon. Thus, they continued to discuss two competing opinions without moving towards resolution. In a design sense, Stat 1 spent too much discussion time talking about the problem, namely, the pros and cons of proposed, yet under-specified ideas. This was a problem for them because design literature suggests that designers, especially novices, should not discuss the problem for too long. Rather, they should pick an option and proceed to craft the design solution fairly quickly (Cross, 2004). The argumentation lesson here is that discussants should seek to agree on *some* common ground (*some* design) in the Opening Stage, and then build upon it by moving quickly into the Argumentation Stage where the original agreement can be refined using knowledge gained after actually having built something.[21]

Specifically for Stat 1, in the Confrontation Stage, the team established two competing opinions: rotating shooter versus fixed twin shooters. It may have been better

[21] Bucciarelli (1994) discusses this discursive process among engineers but without the framework of argumentation, per se.

for then to have picked one—perhaps the one that a majority of the members could manage to assemble, even if they remained skeptical about the outcome—and proceeded to assemble it. In this way, they may have gained some necessary tacit understanding of the mechanical systems in order to make a more informed choice as to which of the two design ideas would be more feasible.

Overall Review of Pragma-Dialectics Stage Analysis

My overall conclusion from this PD stage analysis for sample disputes in Rail 1 and Stat 1 is that the students did, in fact, engage in argumentative discourse that can be parsed into the four stages described in PD theory. These analyses corroborate the findings from the pilot analysis, which showed that the Rail 1 team engaged in argumentation when analyzed from the perspective of scientific argumentation (Berland & McKenna, 2010). In this dissertation's analyses, both teams—Rail 1 and Stat 1—were working toward resolution-oriented discussions, but attaining resolution solely through talk appeared frustrated by their fundamental lack of understanding of the systems they were designing. In itself, this lack is not surprising; what might be more surprising is that despite this lack of understanding, both Rail 1 and Stat 1 did manage to complete a design. They did argue in a more or less collaborative way; however, to speak candidly, it did not appear to get them anywhere.

For example, Stat 1 was right to be concerned about the accuracy of a robot shooting from a rotating platform (6, 67), about how the axle would interface with the platform (4, 41), about the number and orientation of the wheels supporting the platform (1, 13), and about whether one motor would be powerful enough to make the platform rotate (6, 56). They were right to be concerned about the complexities of sorting variously colored balls[22] into the fixed shooters (3, 22). Rail 1 was right to be concerned about the size and placement of the Funnel—e.g., Rail 1 (2, 7) (2, 9) (5, 51). They were right to wait to use Lexan for the House (not described in above analysis). These were all important and correct concerns from an engineering standpoint. The problem was that the students were not able to address those concerns or provide compelling justifications without first trying to build their designs for themselves.

[22] The challenge included the requirement of shooting green and black balls into green or black goals.

I draw this conclusion based on the fact that both teams managed to complete a design despite the fact that the nature of their discussion—their argumentation—didn't appear to be leading them to their successful outcomes. Something else was going on.

Section 3: Role of Physical Objects in Online Discussions

SECTION 3 OVERVIEW

I decided to take a new look at the robot subsystem disputes, with a particular focus on Rail 1 as an example. For simplicity I examined only statements that referred to the subsystems Arm, Claw, House, and Drive. Furthermore, I regarded "Arm and Claw" and "House and Drive" as representing two disputes instead of four. Taken together, these two subsystems constitute the entire robot design—the part that moves along the rail (House and Drive) and the part that collects balls (Arm and Claw). These subsystem parts are the subcomponents that have to be built if the robot is to function; hence, they are central to the design and the corresponding argumentative discussion. I eliminated the Funnel subsystem because there never existed a physical representation of the Funnel, and the Funnel discussion stopped well before the team completed the robot. For the analysis that follows, I assessed all the statements for Rail 1 related to these subsystem pairs, and then selected a minimal subset of statements that accurately convey the subsystem dispute from beginning to end.

In a design scenario, the resolution of differences of opinion goes beyond the mere verbal resolution described in PD theory. In design, and particularly in engineering design, there is no successful resolution until the designers' agreed-upon vision of the design and *the designed object itself* come into alignment. Alignment is achieved when the designers agree that the designed object is what they intended it to be, even if the initial plans and the final product differ somewhat in ways the designers deem immaterial. The designers must agree with each other while taking into account that fact that their designed object is the physical representation of that agreement.[23]

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[23] I am considering agreement broadly: agreement under protest is agreement; agreement through acquiescence is agreement.

Object Use by Rail 1: The Prototype Made All the Difference

As I mentioned above, Team Dynamics was one of the more revealing discourse codes for both Rail 1 and Stat 1. In Chart 4-3: Rail 1 Student Team Discussion Code Timeline, Team Dynamics statements appear with high density near the middle of the chart (up to Day 8) and then mostly disappear, with Praise statements rising in frequency instead. This shift occurred with the emergence of an object critical to the Rail 1 team's mutual understanding of their design. Objects played various roles in the team's design process throughout the project, serving as indicators of confusion and as indicators of shared understanding (and as indicators to me as analyst and to the students as team members).

Indicators of Collaborative Struggles

The following statements suggest that the designed object is serving as a marker for a lack of a shared vision of the design, and hence for struggles in collaborating with each other.

a. (4, 47) (Tasks, Progress Reports, Inviting Ideas, Object, Design Elements) (3rd): Also, the claw that you made was sorta messed up so we totally re-did it but if it doesnt look right to you, feel free to change it but tell us what you did.

b. (5, 77) (Progress Reports) (5th): I went ahead and started building a base out of VEX parts, because i didn't know what else to do

c. (6, 86) (Questions, Object, Design Elements) (3rd): so we found the arm but it was really loose, did you guys by any chance loosen it?

d. (6, 91) (Team Dynamics) (5th): I think that the way our collaboration has been going thus far, we might just want to work on separate parts because we keep trying to rebuild what the other class hadn't finished and it ends up being more confusing.

e. (6, 107) (Team Dynamics) (5th): This is really frustrating, atleast to me personally, to not feel like we're an equal part in this group. I'm not trying to attack anybody, even in the slightest, but we need to figure out a way to deal with this better, I'm sure it can be done if we will listen to both sides of the group and actually take the other's ideas into consideration.

f. (6, 108) (Team Dynamics) (5th): but what we accomplish y'all feel it's not good enough and replace it.

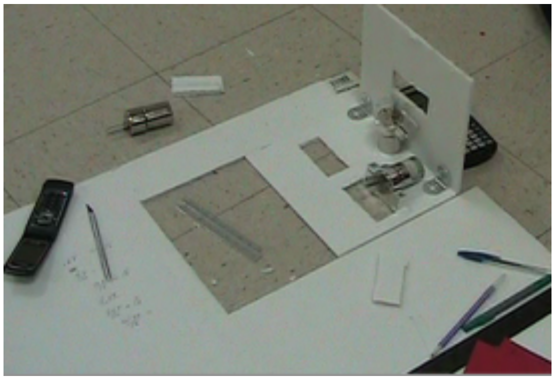
Lines a. and c., on days 4 and 6, respectively, were both made by third period. The statements are examples indicating that third period either did not understand or did not value the contribution of fifth period. The statements indicate their makers perceived problems with the assemblies. Hence, third and fifth periods' visions for the claw and arm were not aligned. Line b. (day 5), shows how fifth period does not understand third period's proposed concept for the base, more commonly referred to as House. Classroom video showed that third period did not understand this VEX base construction when they found it the next day, but third period did not mention that in their online discussion. The Team Dynamics statements (lines d., e., and f.) are representative of the two class periods' collaboration issues, and they directly reflect how each class period did not understand what the other was doing. Fifth period was frustrated and felt dominated by third period; fifth wanted to try something different. Note that in line e., a student asserts that their problems can be remedied by listening to each other. That student was right; however, the discourse analyses suggested that the teams needed a common physical point of reference to more clearly understand what they were saying to each other.

Lines a –f is where the Team Dynamics codes reveal their importance. They illustrate specifically how and why the team had been having trouble resolving its design differences of opinion. That is, the team was struggling to communicate and collaborate, which impeded the resolution process. Note that the timeline (Chart 4-3) showed many TD codes; whereas, I have listed only three. It turned out that most of the TD codes went to reiterated statements or variations on a single theme. The three TD coded statements above demonstrate that theme.

Indications of Productive Collaboration

The following statements suggest that the designed object serves as a marker for shared understanding, hence productive collaboration.

g. (8, 152) (Progress Reports) (3rd): We are also truckin along on a prototype for the drive train and the measurements for the house.



Photograph 4-1: Poster board prototype of the House[24]

h. (8, 156) (Object, Design Elements) (5th): We think that the motors are too far up and will hit the rail impairing movement.

i. (9, 194) (Agreement, Object, Design Elements) (3rd): So the deal was that our wheels WERE too close, like you guys said

j. (9, 184) (Progress Reports, Inviting Ideas, Object, Design Elements) (3rd): Sooooo I finally finished the arm!! but! to me it looks a little bit too long tell me what you think!

Photograph 4-2: Working with the Arm

k. (9, 211) (Object, Design Elements) (5th): we found out that the arm is really too long... I think the second shortest C-channel would work.

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[24] Photographs 4-1 to 4-4 are still images taken from the classroom video I recorded. They are meant to be illustrative, to provide the reader of images of the objects that Rail 1 was making and sharing.

l. (8, 168) (Questions) (5th): So, can some one please tell me why the Lexan is important?

m. (10, 225) (Answers, Design Elements) (3rd): TO Q: the Lexan is important because it has less weight than metal so it wont add weight and unbalance the robot.

Photographs 4-3 and 4-4: Working with the Lexan

n. (10, 246) (Object, Design Elements) (5th): So I finally get the point of the Lexan is to attach the mototrs, I thought it was like going to be superficially on the sides and I didn't understand why it mattered it weighed less than metal b/c I didn't understand the real reason for it.

By day 8, the Rail 1 team's process began to change. Lines g., h., and i. show that third and fifth period began to have valuable insight into the design of the House. Third period began a poster board prototype; fifth period recognized a flaw (line h), and third period agreed that it was a flaw (line i). Similar reciprocity occurred over the Arm (lines j. and k.). In lines l., m., and n., the value of the Lexan for construction of the House was finally understood by both class periods.

The Lexan was third period's idea, but their justification for its use had to do with weight (line m.). However, in line n., fifth period, after just realizing the Lexan's purpose, stated that it was for attaching the motors. It turns out this is a more accurate, if incomplete, interpretation. The Lexan offered a contiguous surface area, which allowed the students to place the motors precisely where they needed to be in order for the wheels to contact the rail properly, and the Lexan is stiff enough that the wheels wouldn't move once they were in place. The TETRIX parts are skeletal, and don't offer such precise placement of parts. It wasn't until day 8, however, that third period convincingly explained the tacit knowledge they may have held about the Lexan properties. The convincing argument was the poster board prototype. It mimicked the Lexan's function well enough that fifth period could see that something like poster board that was harder and stronger (i.e., Lexan) would satisfy their design requirements. Throughout the discussion, the reasons behind using the Lexan remained implicit until a physical object could be constructed to demonstrate the students' reasoning.

The preceding exposition is meant to demonstrate how the students in this robotics class were focusing on their physical objects and using them as the primary vehicles and indicators for progress and team collaboration. Evidence of this practice can be found in the online discussions of Stat 1 and the other five teams; Rail 1, however, provided the clearest example of this phenomenon. For Rail 1, the emergence of a prototype House marked significant shifts in their discussions and in their design process. The object became the key to developing a shared understanding that enabled the teams (in their two separate class periods) to start collaborating productively. The object also became central to the students' argumentation, carrying information that the students could not articulate but that was essential for their arguments to be understandable and convincing.

A New Taxonomy of Object-Based Claims

In scientific argumentation—and other forms of argumentation—we think of objects as sometimes optional affordances for consensus building. But in engineering design, and in design considered more broadly, objects serve a privileged role because they serve both as *affordances* for arriving at consensus and as *representations* of that consensus.

The privileged role of objects in design contexts is situated within the cultural practice of deferring to an object's form and function—that is, whether or not "it works." Bucciarelli's engineers collectively deferred to a designed object that "does the job" (1994, p. 153). For a design to "do the job," however, its form and function must adhere to precise, measurable requirements that may become articulated through an iterating negotiation process in which the engineers and the designed object play crucial roles.

The engineers must negotiate toward a compromise that honors the wishes of multiple engineers (and, often, other stakeholders as well)—each operating from a different object world—and that attains the measurable (or at least observable) desired performance of the object itself. The engineers' goals and the object's performance (that is, its form and function) evolve concurrently. As noted in Chapter 2's literature review, this idea, of course, is not new, and Chapter 2 overviews what is known about the relationship between object and designers as that relationship unfolds in the engineers' design discourse.

In this dissertation study, I observed students in the early stages of the pedagogical and acculturating process through which they were becoming novice engineers. During this process, the students appeared to significantly privilege their designed objects in seeking to understand their own ideas, to communicate ideas, and to facilitate consensus. But it was not just ideas about the objects at hand that were important to their deliberations; it was the students' interactions with those objects through visual, tactile, and functional channels.

What I found was that the students were making claims, the evidence for which was best—most clearly, most efficiently—conveyed through the object itself and which had to be interpreted through sight, touch, or intended function (for the robot challenge, in a designerly sense with respect to other subcomponents of the designed system). The students did not, or could not, articulate necessary design evidence in their online discussions, at least not convincingly to their peers. It is sometimes the case in engineering design that the physical object's ability to convey critical information has no substitute (Bailey, Leonardi, & Barley, 2010), but it was certainly the case for these students that the physical object was indispensible for carrying critical and convincing information.

The idea that there exists important information that can best (and sometimes only) be conveyed through objects or drawings is not new (Bucciarelli, 1994, 2002; Henderson, 1999; Schon, 1983). What is important here is that if argumentation is to be used as a pedagogical tool in engineering design, then the argumentation structure must allow for a verbal and written argument structure that coexists with the artifacts the designers are using, and, in particular, the designed object itself. An argument should be able to carry meaning through a cohesive union between words and object—a union in which neither component is dispensable.

During the development of pragma-dialectic theory, Van Eemeren and Grootendorst (1984) described argumentation as a complex speech act in which locution, illocution, and perlocution play significant roles in resolving differences of opinion. If PD is used as an argumentation model for enhancing the communication necessary to team engineering design, then *physical artifacts* should be included as "speech acts" within the definition of argumentation. Bucciarelli (2002) argues that the artifacts engineers use are linguistic and that in the midst of engineering design negotiations, these linguistic artifacts have multiple meanings or interpretations, depending on an engineer's own object world. This semiotic reality of engineering artifacts is parallel to the linguistic reality of illocution and perlocution. Therefore, I believe that the two theories could merge to form a cohesive theory of argumentation in engineering design.

For now, however, I will proceed by defining the three categories of Object Claims that emerged from the students' online discussions.

CATEGORIES OF OBJECT CLAIMS[25]

To further characterize an argumentation structure in which meaning is created through the union between words and objects, I have defined three types of claims. These definitions derive from results of this dissertation study specifically and supporting literature. As claims, the following categories exists as part of the overall argumentation structure that encompasses the resolution of differences of opinion within a design discussion. The three categories are as follows:

Establishment Claims

- Keystone object claims
- Tinkering object claims

Constraint Claims

[25] PD theory doesn't promote the terms *claim* and *evidence* as necessary features of argumentation, but within the bounds of PD theory, the terms are acceptable as components of argumentation. In this section I will use both *claims* and *evidence* to clarify communication and to expand upon a common structure of scientific argumentation.

- Tactile constraint claims
- Visual constraint claims

Counterfactual Claims

- May serve as both establishment and constraint claims

Establishment Claims

I define *establishment claims* as assertions that an intermediate design step has been or should be established. These could be, for example, statements of what has been done or what needs to be done in order to further the design. *Establishment claims* by definition relate to the designed object, and thus do not relate to managerial concerns or team relations, per se.

I define two establishment claims: *keystone* and *tinkering.*

Keystone object claims

Keystone claims are assertions that something is a preferred intermediate step towards the completion of the design as a whole. The intermediate step may already exist as a physical object, or it may have yet to be created.[26] My motivation for the keystone category was that the students seemed to use one subcomponent of their design as a point of reference from which to envision, design, and build other subcomponents. A *keystone claim* derives its meaning from both words and objects. The relative contributions towards that meaning may change, depending on the situation.

A *keystone* claim, then, can be seen as a reification of one or more proposed possibilities among the web of possible design moves; the keystone claim derives from the designers' knowledge and imagination—and the current status or configuration of the design. When it is reified through a *keystone* claim, the object becomes fixed (e.g., as a subcomponent), and the designers then proceed to use it as a foundation for further design moves (often involving other subcomponents). However, as the design evolves,

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[26] The term *keystone* has multiple definitions, both physical and figurative, and for background I here present three :

> **1.a.** A central stone at the summit of an arch or vault, locking the whole together.
> **1.c.** *fig*. The central principle or element of a system, ideology, etc., on which all the rest depends; a vital or essential part of something.
> **3.** *Building*. A stone placed transversely so as to connect the inner and outer layers of a wall;
> (Oxford English Dictionary, Third Edition, December, 2012. Accessed on July 13, 2014)

any *keystone* claim, as a physical manifestation may still need to be adjusted or modified to meet emerging constraints and to fit within the design as a whole. *Keystones* are not immutable; but regarding them as fixed, at least for the time being, is an important step in the design process and associated design negotiations.

I chose the word *keystone* because I could not find an existing term of art in design for the exact object-based claim I describe, and because of keystone's architectural and figurative foundations. *Prototype* (Subrahmanian et al., 2003) and *mock-up* (Bucciarelli, 2002) were candidates, but these terms refer strictly to the object itself (or, in a broader sense, to a representation of an object). I needed a term that served to identify a coherent relationship between text and object—inseparable linguistic and physical elements of an argument.[27] Defined as such, I believe that *keystone* claims fit within Schon's concept of design as conversation (Schon, 1983).

The following are selected keystone claims from the online discussions. Indented text constitutes verbatim quotations from students. My comments, in square brackets, follow each quote.

> Rail 1 (3, 26) (3rd): If you guys want to make a funnel that's cool. It may be difficult though because we won't have a frame to build off of yet, nor material to build the funnel out of.
>
>> [Asserts "frame" as a keystone, and implies that the Funnel will require tinkering to adjust it with respect to the frame.]
>
> Rail 1 (3, 22) (3rd): So I think we're going to start with building the arm because we have the materials, we are sure of the plan, and we basically build everything else off of the dimensions of the arm.
>
>> [Asserts the Arm (subsystem) as a keystone.]
>
> Rail 1 (1, 2) (3rd): if we build the base first we will be able to adjust all of the other components to a size that will work well.
>
>> [Asserts the base (or the House subsystem) as a keystone.]
>
> Rail 1 (9, 215) (5th): once we get the Lexan done we'll see how to attach the arm.

[27] I acknowledge that I am on the verge of two theories: *boundary objects* (cf. Star, 1989) and *activity theory* (cf. Engestrom, 1999). Both may be relevant, but incorporation of either is beyond the scope of this dissertation.

> [Lexan as keystone; it is a primary component of the base (House).]

Stat 1 (1, 9) (5th): i would agree with building the base first in order to have something to build on for both groups.

> [Asserts the base (subsystem) as keystone.]

Stat 1 (4, 33) (3rd): The whole construction will only proceed when the sheet metal is attached and the rest of the robot such as the funnel and the shooter can be attached upon.

> [Asserts that the sheet metal is a keystone, which further established the base as keystone because the sheetmetal in an integral component of the base.]

***Tinkering* object claims**

Tinkering claims are linguistic markers for process(es) through which a *keystone* is developed—or through which other design components are developed, possibly with respect to the *keystone*. A *tinkering claim* derives its meaning from words, and a process that relate to some specified physical object. *Tinkering claims* do not necessarily prescribe the physical outcome of the tinkering process to which they refer.

I chose the term *tinkering* because the word was used in Rail 1's discussion and because of the important role tinkering plays in active learning. Mitchel Resnick (2003) describes the tinkering process:

> I think when you are in the process of creating something… it's often taking a model that you have in your mind and playing out that model with a new creation in the world. But as soon as you create something in the world, it's not necessarily going to live up to exactly the model that you had in your mind. It will disagree in certain ways or surprise you in certain ways. So by creating things in the world, it leads you to revise the models that you have in the mind. And as you revise the models you have in the mind, it leads you to create new things in the world. So I think that we think about this constant cycle back and forth… it gives us an opportunity to test out, to try out, to play with the models we have in our mind and continually iterate back and forth between the two (pp. 1–2).

Tinkering, then, is a process that entails ongoing exchanges between mental representations and their physical instantiations. Tinkering is typically something that people *do*, as opposed to something that they *say*. For the purpose of this dissertation, a *tinkering claim* is something that appears in the discourse as a linguistic marker that tinkering is called for, is ongoing, or has already occurred.

The following two quotations assert that *tinkering* will be required for certain parts or subcomponents which, in these examples, are not *keystones*.

> Rail 1 (6, 104) (5th): Also we have to work on where the basket is positioned and where the stationary robots are positioned to figure out if the basket is going to work.
>
> [Tinkering for the basket (aka. Funnel) with respect to the partner Stationary robot.]
>
> Rail 1 (3, 24) (3rd): The claw is a very changeable part, so when we get to building it we can basically do anything we want to it.
>
> [Tinkering (implied) for the Claw; the Claw is not a keystone.]

***Constraint* Claims**

Constraint claims identify physical realities or observations about the environment that articulate the constraints—the things that must be attended to—in the development of a keystone, possibly through tinkering. Constraints, also known as design constraints, provide the designers with cues by which they can determine whether the design (or a subcomponent thereof) is "doing the job." I define constraint claims as either *tactile* or *visual*.

Tactile object claims

Tactile claims identify physical realities or environmental observations that must be perceived through touch. Note in particular the underlined words (author's emphasis) in these quotations from the online transcripts.

> Rail 1 (3, 37) (5th): I really like how the arm works with the gears, <u>but it's not fluid</u>, how can we fix this?
>
> Rail 1 (6, 111) (5th): So, i experimented with the arm today for almost an hour and could not find a way to have the second joint fixed in place or tight in the hole. <u>I do not know why the first joint is sturdy, but the second joint is extremely lose, even though it looks exactly the same.</u>
>
> [This is not a visual claim because the emphasis is on the feel.]
>
> Rail 1 (12, 281) (3rd): the arm is <u>proving to not like working for us.</u>

Stat 1 (14, 170) (3rd): we have also decided to use poster paper for the ramp instead of Lexan cause its easier to deal with

Stat 1 (14, 172) (3rd): well i spent the period fixing the shooter. many of the peices werent fastened correctly and needed to be switched out it runs relatively smoothly now.

Visual object claims

Visual claims identify physical realities or environmental observations that must be perceived by sight.[28]

Rail 1 (8, 157) (3rd): Secondly, we cut out a prototype of the house/frame. It's pretty bad ass. Hopefully it will give you guys a better understanding! Please don't change any of the dimensions on the prototype because it took a while to figure those out.

[I interpreted this statement to include the unwritten implication that the understanding would come after seeing it.]

Rail 1 (10, 238) (3rd): It is starting to look really good and we are getting closer to the final product!!

Rail 1 (5, 53) (3rd): we have worked on troubleshooting the arm today. When we found it this morning, we found that when the arm moves, metal flakes fall from it. We basically took the robot apart, piece by piece and inadvertently fixed the problem but noticed a problem with the spacing between the two parts of the arm.

Rail 1(9, 193) (3rd): we made a prototype out of foam board so we could mount parts (it looks like our robot yay!)

Stat 1 (9, 107) (5th): We haven't seen anything extra being built. Because of this we are just going to continue building our design.

Stat 1 (13, 152) (3rd): and i think the other launcher was mounted on the lexan upside down.

Stat 1 (14, 171) (3rd): to-do 1)attatch the ramp to the frame at the top on the skinnier side of the poster board and the bottom of the shooter on the wider side of the poster board

Taken together, these four categories of object claims (keystone, tinkering, visual, and tactile) provide a useful taxonomy for analyzing argumentation in an engineering context. The object claims I have described fit within the four-stage model for resolving

[28] There could be aural and olfactory claims as well, but the students did not use them.

differences of opinion, according to pragma-dialectic theory. All four object claims could most likely be categorized in the Argumentation stage of pragma-dialectic analysis, but, depending upon the intentions underlying them, could also work within the Opening and Confrontation stages. They don't strike me as elements of the Concluding Stage, but this is merely speculation at this point. It is my hope that these four categories of Object claims may enable an understanding of design communication as argumentation in which both spoken and written discourse as well as physical (e.g., the object) elements coalesce to become tangible and meaningful.

Counterfactual Claims

I believe that there is an additional type of object claim, which I term *counterfactual* claims, that could serve as both establishment and constraint claims simultaneously. Counterfactual claims are logical and take the form "if…then" statements; they propose the establishment of some design idea or modification ("then") that can occur once certain constraints are met ("if"). Counterfactual claims may also address functional design goals: e.g., *if* we (the designers) make the following changes, *then* we can achieve some desirable functional or performance goal. When describing how the process of *framing* is a key aspect of design reasoning, Dorst (2011) offers what I consider to be a generalization of *counterfactual claims:*

> IF we look at the problem situation from this viewpoint [as in viewpoint X], and adopt the working principle associated with that position [viewpoint X], THEN we will create the value we are striving for (p. 525).

As I explained in Chapter 2, counterfactual exercises are common among engineering designers and are alluded to, and addressed explicitly, by researchers in design (Dixon and Johnson, 2011; Dorst, 2006, 2011; Harrison and Minneman, 1996). Such exercises often incorporate drawings (Schon, 1983, 1992), physical mock-ups or prototypes (Bucciarelli, 2002), visual and/or tactile inspection (ibid.), and information from test results and mathematical models (ibid.). Because *counterfactual claims* can be informed by information ranging from visual inspections to mathematical models, they may derive from both intuitive thinking and analytical thinking. Hence, *counterfactual* *claims* are accessible to any level of designer, from "naïve" to "visionary" (Dorst, 2011, p. 526) *Counterfactual claims* are intrinsically logical and provide a bridge between the physical world of what does exist and the mental world of what could exist (Hilpinen, 1993).

Below are some examples of *counterfactual claims* from the online discussions. Again, I have included this category largely as a matter of theoretical consistency with design literature. Rarely did any student use the closed form, "if [this]…then [that];" however, the spirit of counterfactual exercises may be recognized in the following excerpts. Perhaps more advanced students would use the closed form more readily.

> Rail 1 (1, 2) (5th): I would also add some sort of rubberband type of material so that it's easier to grip the balls.
>
> > [*If* we add rubber, *then* easier to grip balls.}
>
> Rail 1 (2, 18) (5th) I'm worried that the L-brackets might not be long enough to be able to grab the balls efficiently, and that the probability that the balls will slip off is high. I suggest that we have an extension out of the L-brackets by using the flat brackets.
>
> > [*If* we extend the L-brackets, *then* the balls won't slip out.]
>
> Rail 1 (3, 40) (5th): The arm looks like it has a small margin of error, so I am going to look for something bigger or wider that will be more reliable. I was considering bending some plastic that will cup around the ball making it easier to pick the ball up.
>
> > [*If* we cup the ball with plastic, *then* it will be easier to pick up.]
>
> Rail 1 (4, 48) (3rd): I think the arm will be better with the motor on.
>
> > [*If* we mount the motor, *then* the arm will be better.]
>
> Rail 1 (5, 51) (3rd): Instead of doing a funnel why cant we just have the robot pick up a ball and it goes to the place where the stationary robot is and drops it? Wouldn't it be easier?
> Rail 1 (6, 81) (3rd): I think that if we just have the arm hold the ball it would be difficult to program.
>
> > [*If* we pick up one ball at a time, *then* it will easier than the funnel, but difficult to program.]

Rail 1 (5, 70) (5th): So we had some concerns about the length of the arm. I think that it's going to be a little long depending on how we attach it to the base. <u>if we mount it so that the entire arm is vertical the arm as is is too long. if we mount it horizontally so that the part with the motor is horizontally attached to the base of the robot, the arm is the right length but we have the issue of the adding the claw and the length of th claw.</u> I personally think that we should make the arm itself shorter so we can make the claw longer.

[An example of the *if…then* form.]

Rail 1 (6, 81) (3rd): but the basket-thing may be a little big also but not quite as big as the funnel. i thought that if we do make a basket then it could be angled you so the balls don't fallout of it like it would if it was not tilted. but for the basket it would be easy to program all it has to do is tilt the back up so the balls come out and into the stationary robot. i really do like the idea of the basket but it's up to everyone

[*If* we make a basket, *then* it would be easier and smaller (i.e., won’t get in the way)]

Rail 4 (2, 7) (8th): However, I think you are right to worry about the claw. We now see, after more discussion, that our idea of using bent plastic is too hard. We are thinking of a more easy to build one, made out of metal more like yours. We are thinking of bending flat plates of metal to pick up the ball.

[*If* we use plastic, *then* it will be too hard. *If* we use metal, *then* it will be easier.]

Rail 4 (2, 23) (8th): We can also add rubber bands on the sides to make sure the balls don't slip out of the claws.

[*If* we use rubber bands, *then* the balls won’t slip out.]

Stat 1 (1, 6) (3rd): Also, the shooter looks perfect but couldn't you make it a little shorter? It will help the robot rotate faster and everything

[*If* you make the shooter shorter, *then* the robot will rotate faster.]

Stat 1 (1, 13) (5th): How will the base of the robot rotate? Currently I just see that there are 3 wheels all facing in the same direction with no motors powering it and don't understand how it is supposed to function. I suggest that if you still want it to rotate that it should have 4 wheels instead of three so that the rotation would be simpler.

[*If* you want it to rotate, *then* you should use four wheels.]

> Stat 1 (4, 41) (5th): Ok I like what i'm hearing for how it rotates, that makes a lot more sense. But have you considered how the axle might create too much resistance when it's rubbing up against the platform? If not, using a buffer of some sort might help.
>
> > [*If* the axle rubs against the platform, *then* it will create too much resistance.]
>
> Stat 1 (5, 49) (5th): Maybe instead of using foam for the bottom of the launcher, we could use any sheet metal that we have left. That way the balls could have less resistance prior to shooting. Is there anything else we should work on today besides the shooter?
>
> > [*If* we use sheet metal instead of foam, *then* the balls will have less resistance.]

Interpreting the above statements as *counterfactual claims* required me to read more into the statements than I had done for previous coding efforts. Such interpretation isn't without precedent (cf. Resnick et al., 1993), and doing so aligns with pragma-dialectic principles (van Eemeren & Grootendorst, 2004). However, as a single analyst working with a brand new scheme, I will not draw further conclusions about the students' argumentation structure based on these new "codes." Rather, the three categories of *Object Claims* are themselves conclusions resulting from my analysis in this dissertation. The above lists are examples demonstrating that the *Object Claims* exist (with some interpretation) within the students' online discourse, and that these claims may be used in future research and perhaps pedagogical scaffolding.

That said, in the next section, I will use some of the *Object Claims* as codes—a trial run—to aid an examination of team Rail 4's treatment of their physical object.

Section 5: Analysis of Team Rail 4

The following is an examination of team Rail 4 team's design process to assess what (and how much) effect the Rail 4 drawings had on this team's privileging of their physical objects in their design discourse. This analysis is a test against the primacy of physical objects found in the discussion of Rail 1 and Stat 1. In other words, without detailed or serviceable drawings, Rail 1 and Stat 1 may have placed primary importance on their physical objects purely out of necessity. Without that necessity, Rail 4 may have viewed their physical object differently or placed less importance on it.

Rail 4 had access to useful drawings and a team member who was able to update those drawings as needed. In contrast, teams Stat 1 and Rail 1 had created, and were working with, drawings that they felt were not as useful as they would have liked them to be—and they were unable to update their drawings in a timely manner. Thus, I must consider the possibility that the apparent primacy that Stat 1 and Rail 1 gave to their physical object in resolving design issues could have resulted from the absence of useful drawings, rather than from the intrinsic qualities of the physical object. Because Rail 4 possessed more serviceable drawings, that team may have given their physical object less privilege in their design and argumentation processes. An examination of Rail 4's discourse to determine how they engaged with and used their designed objects may help reveal whether Rail 1 and Stat 1 privileged their design objects simply because they lacked other resources (e.g., high quality drawings).

Privileging physical objects due to an absence of other representations (drawings) does not necessarily diminish the central role that physical objects play in students' acculturation towards becoming novice engineers. In fact, professional engineers continue to turn to physical objects for information and insight even in the presence of sophisticated drawings and models (Bailey, 2010). Designers create and work with physical objects prior to or alongside creating and working with drawings (*Objectified*, 2009). However, the data I have analyzed—in particular, for the two focus teams Rail 1 and Stat 1—have led me to conclude that students privileged physical objects and that such privilege may be crucial to the development of engineering designers. Because my data offer at least one example of a team that seemed able to leverage their drawings more extensively, it's worth examining that team (Rail 4) as a special case.

I begin by reviewing Chart 4-1: Distribution of coded statements across all six student teams.

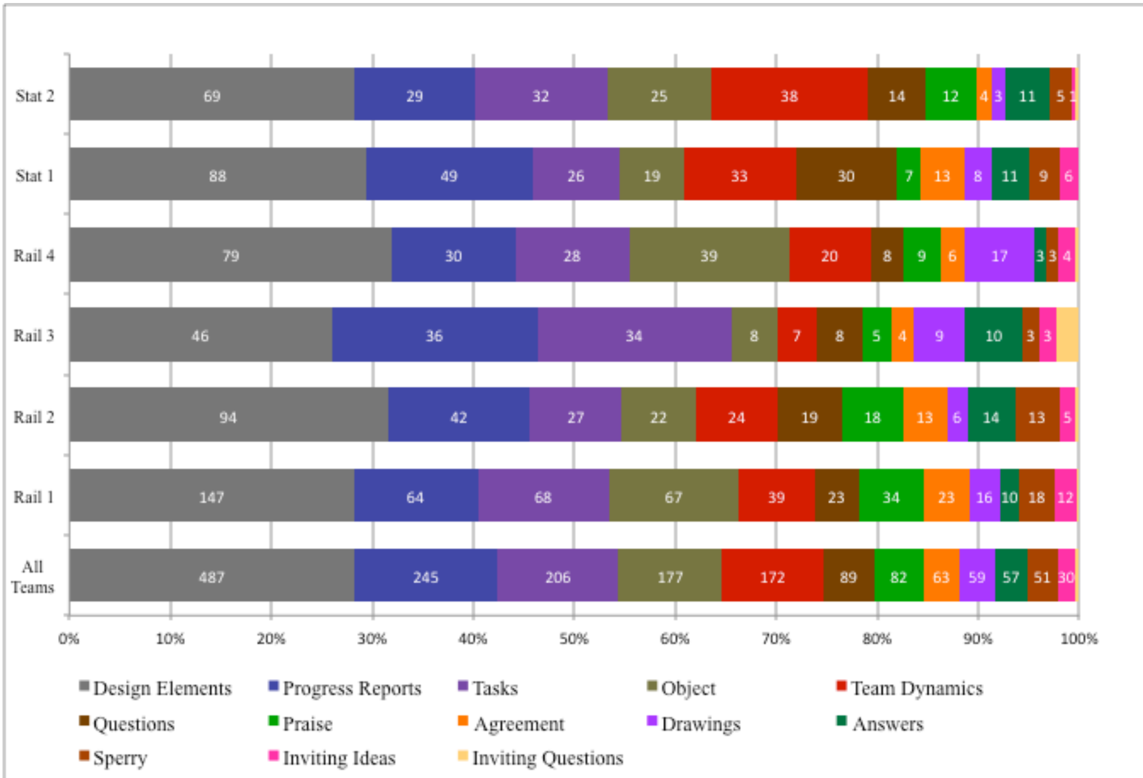

Chart 4-1: Distribution of coded statements in online transcripts for all six teams

For each colored block, the number inside the block is the number of statements (n) having that particular code, and the width of each block represents the percentage of that particular code within all coded statements for that team. For Rail 4, Object (olive green, n = 39) and Drawings (light purple, n = 17) occur at a higher percentage than in all other teams (and the aggregated All Teams). In other words, statements coded as Object or Drawings occurred more frequently in Rail 4 than they did in any other team. (For reference, Rail 1 had 522 coded statements, Stat 1 had 299, and Rail 4 had 247.) It is also the case that Rail 4 had a higher percentage of Design Elements codes than did either Rail 1 or Stat 1. Taken together, the higher percentage in Rail 4 of the three codes (Design Elements, Drawings, and Object, which make up the Design category described in table 4-3) suggests that Rail 4 dedicated more of their online discussion to design-specific statements than did other teams. The quality of Rail 4's drawings may have influenced these higher frequencies of Design Elements, Drawings, and Object codes.

Now I will review the code timeline for team Rail 4, and I will focus my attention on the codes within the orange box: Design Elements, Drawings, and Object (the Design category). Taken together, Chart 4-1 and Chart 4-6 (the timeline for Rail 4) suggest that Rail 4 may have had a different experience with their drawings than did teams Stat 1 and Rail 1.

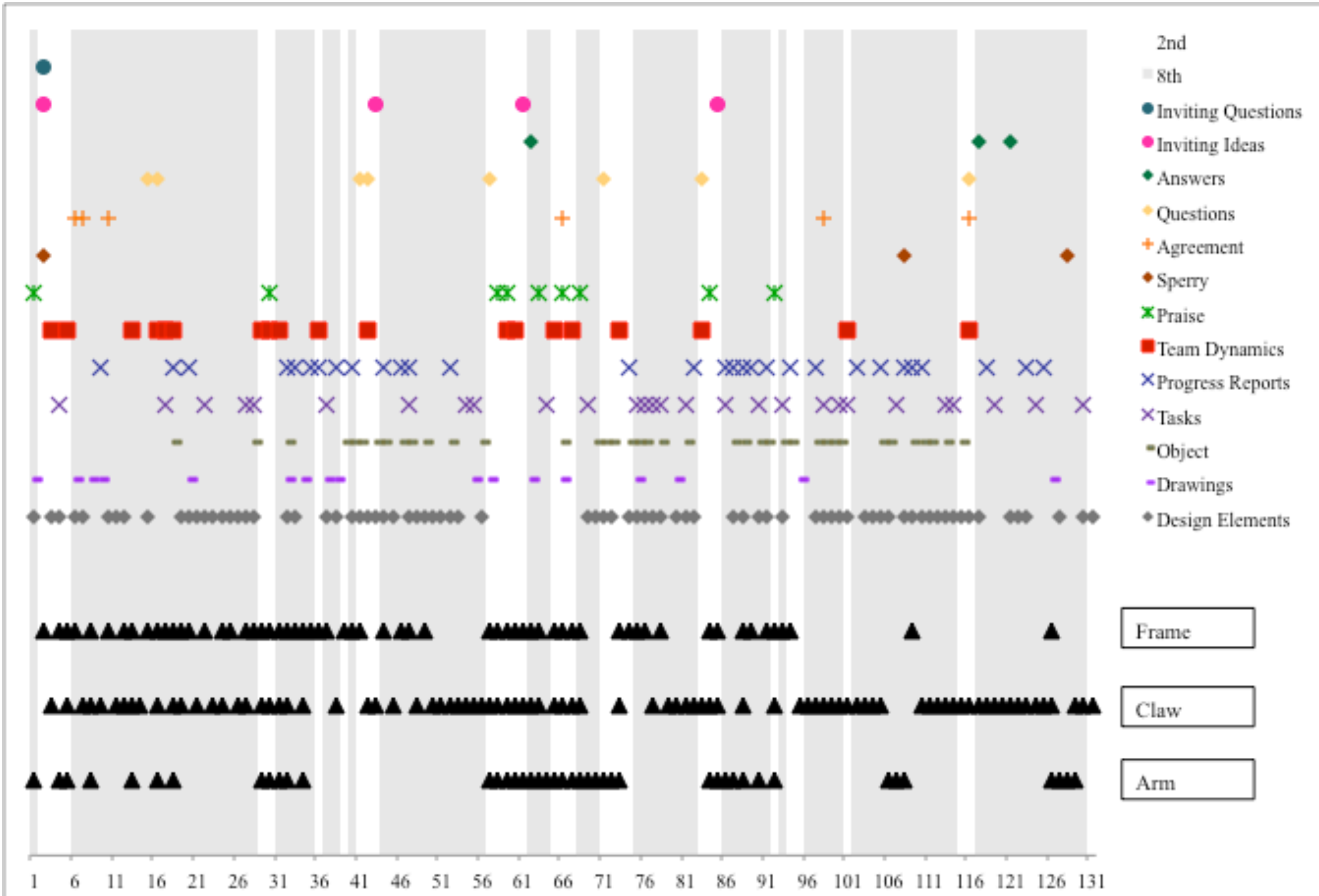

Chart 4-6: Rail 4 Student Team Discussion and Subsystem Code Timeline

Design Elements codes appeared frequently across the entire timeline—from the beginning through the end of Rail 4's online discussion—a pattern also evident in the timelines of Rail 1 and Stat 1. Drawing codes for Rail 4 appear with more or less regular frequency, beginning on line x=1 and ending (except for that one at the far right)[29] at about line x=96. Object codes also appear with some regularity (and more frequently than Drawing codes) beginning near line x=16 and terminating near line x=116. Note that the frequency of Drawings codes skews to the left (beginning of the discussion), and the frequency of Object code skews to the right (ending of the discussion). It appears that Rail 4 began their discussion by referencing their drawings, then their drawings and their designed object (possibly in concert), and then finally (mostly) abandoned their drawings in favor of working directly with the object itself.

I believe that for a robotics class, this progression—from the more abstracted rendering in drawings to the less abstracted rendering as object—is optimally efficient: begin with a set of drawings; use those drawings to assemble much of the robot, and then address the assembled robot directly for final assembly, trial runs, and adjustments. I also believe that such an efficient design and assembly process, governed by detailed drawings, may not equate to a rich and valuable learning process for every student. In robotics, and perhaps in engineering design generally, a messy, even somewhat haphazard design process may be particularly beneficial to the student who is learning to balance the use of intuitive and analytical thinking.

Another feature of Chart 4-6 worth mentioning is the number of coded statements contributed by period 2 (white background) versus the number contributed by period 8 (gray background). Period 8 contributed significantly more coded statements than did period 2. The wide discrepancy warrants further investigation. The entire online discussion was conducted by seven students. My analysis sheet for Rail 4 consists of 131 unique statements that I extracted from the coding of the entire content of the online discussion. (As with the analyses for the other teams' online discussions, each statement may have been assigned multiple codes, hence the total discourse code count for Rail 4 was 247.) Table 4-4 shows the distribution of discourse codes across individual students in Rail 4.

[29] This one is a reference to the drawings as an assignment, not as a design tool.

	Period 2			Period 8			
Student Identifier	A	B	C	D	E	F	G
Number of Coded Statements	17	9	7	50	25	15	8

Table 4-5: Distribution of Statements by Rail 4 Team Members

Student D from period 8 had by far the greatest number of coded statements (i.e., statements that received one or more codes). To be clear, each team member contributed at least one post per day, as instructed; however, students D and E contributed posts that were longer and more densely packed with information. Hence, their posts received more codes than did others. It appears that students D and E may have dominated the discussion.

DESIGN DRAWINGS FROM RAIL 4'S DESIGN PROPOSAL

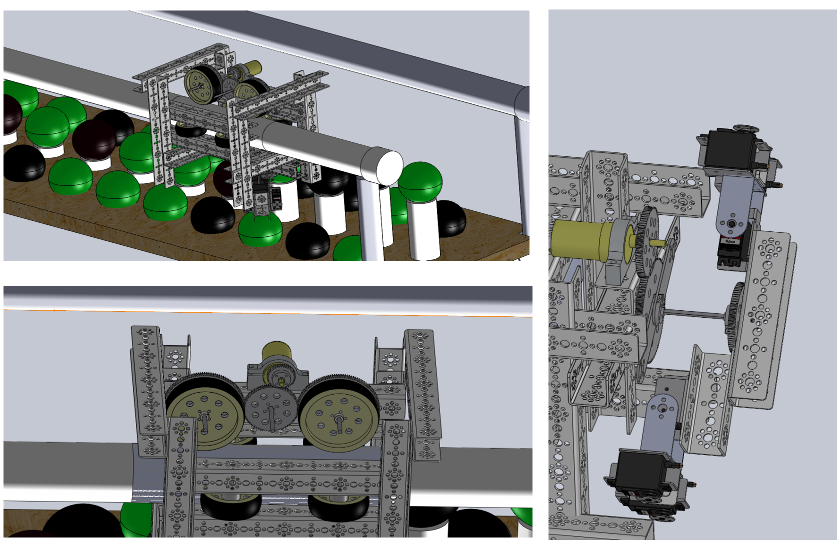

Figure 4-2: Rail 4 Design Proposal Drawings

The images from Rail 4's design proposal show greater design detail, better integration of subsystems, and (unique to Rail 4 among all six teams) a sense of perspective for the robot relative to the game apparatus. It turns out that student D (Table 4-4) created and updated the CAD drawings. Further, student D inserted updated drawings into the online discussion—a technical feat no other student was able to accomplish—that included instructional labels.[30]

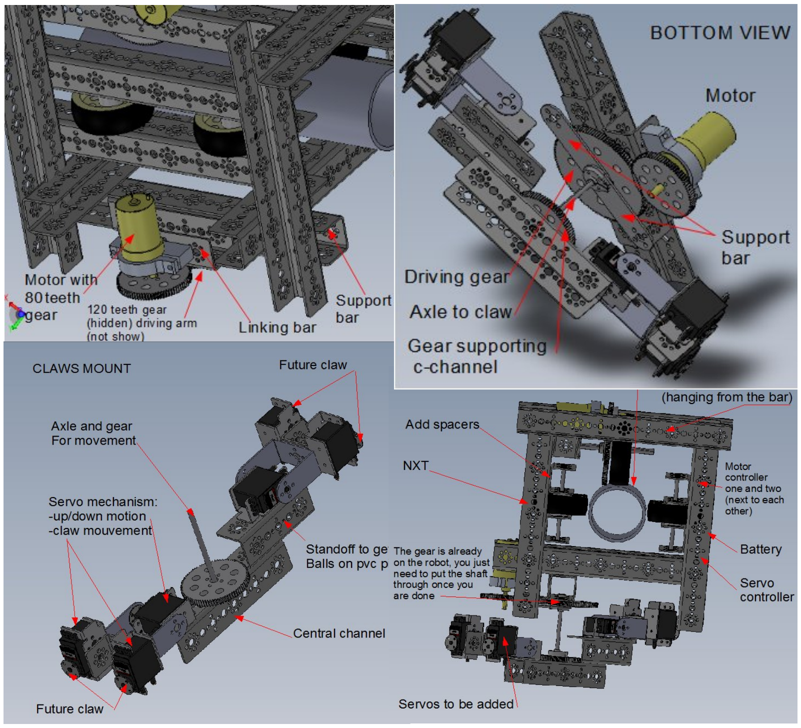

Figure 4-3: Rail 4 drawing updates from online discussion

I now turn to statements from the online discussion, with a focus on Object and Drawings codes to determine how much Rail 4 privileged their physical object. I will present Rail 4 quotes in five subsections: a) tests on the game apparatus, b) *visual* and *tactile claims*, c) *keystone claims*, d) language precision promoted by the drawings, and 5) perspective from the CAD creator.

a) Four test result statements called for or reported the results of tests of the robot assembly. These activities could only be accomplished through interaction with the physical object. The following four statements help to show that interaction with the object was necessary.

---

[30] Wow!

> (4, 47) (Object, Design Elements) (8th): We fininsh the frame and mounted the wheels to the side, though we didn't had time to test it. This is what you should do at first.
>
> (5, 74) (Object, Design Elements) (2nd): Today we actually put the frame on the pvc pipe to see how well it would fit and other nit picky things, so far so good.
>
> (7, 88) (Object, Design Elements) (8th): Today we made some adjustments to the robot after we did tests on the actual rail.
>
> (9, 115) (Object, Design Elements) (2nd): the claw, at least when i tested it seemed to be able to hold the ball pretty well.

b) Seven *visual or tactile claims* occurred showing that the Rail 4 team was interacting with the physical object to modify and finalize their design. Doing so isn't remarkable in the context of robotics design; the point is that tactile claims occurred even though the students also had access to detailed drawings.

> (4, 39) (Object) (2nd): With the time constraints of today, we decided to look at the physical design you already created. We are concerned that the robot may be too wide for the alloted space on the rail. [*visual claim*]
>
> (6, 78) (Object, Design Elements) (8th): Finally, on the side with the red tape, the thin spacers between the frame and the wheels need to be change to bigger spacer to get the alignment right. [*visual claim*]
>
> (7, 72) (Object, Design Elements) (2nd): The last concern I have is that the arm of the robot seems to be extremely flimsy. We will try to think of ways to fix this and update if we get any ideas [*tactile claim*]
>
> (7, 90) (Object, Design Elements) (8th): As [student] said, the arm and claw are heavy. So we are going to put all the electronics on the same side. [*tactile claim*]
>
> (7, 93) (Object, Design Elements) (8th): Also, check the drive train, some shaft collars were loose, causing the wheels/gears to move. [*tactile claim*]
>
> (8, 104) (Design Elements) (8th): We also need to make sure it's balanced and we have counterbalances for the weight of the claw. [*tactile claim*]
>
> (8, 94) (Object) (2nd): Also one of the wheels was super loose so we tightened it, everything should be good now. [*tactile claim*]

c) Three *keystone claims* showed varying preferences for establishing the Rail 4 subsystems of Frame or Claw(s) as the preferred keystone. The Claw subsystem was never shown in the drawings.

> (2, 19) (Design Elements) (8th): Also, we should build the claw last so that we can adjust it to the frame, not the other way around.

> (2, 22) (Design Elements) (8th): So I think we should start by building our frame (on Friday), the adding the drive train with 2 motors once it is done and working, then finishing with building the claw, once we are sure of the design we want to use.

> (2, 24) (Design Elements) (8th): I think the final design of the frame should be decided after we choose a claw design so that space and other factors can be taken into account, so lets not focus too much on the frame.

d) Some statements indicated the existence of detailed drawings through the use of precise language not found in other groups' discussions. Note that statements (2, 9) and (2, 11) occurred on day 2 and included measurements as fine as 1/2 inch. Note that this level of detail appeared comparatively early in the discussion for Rail 4.

> (2, 9) (Drawings) (8th): I build the solidworks on the field, itself build from the actual field, and I might have made some measurement error when building the field. However, 2in seems too much.

> (2, 11) (Elements) (8th): I think this is because our claw is not centered under the robot but a little to the side to compensate the weight of the motor on the other side. This might be the problem. Also, we design the claw so that there is 1/2 an inch between the servo and the ball so we can put the claw. Taking this into account, I think the claw is the right side, but might be wrong.

e) The creator of the drawings revealed his or her judgment on how to best make use of drawings: drawings are a conceptual guide and not necessarily a direct representation of the physical design.

> (4, 34) (Drawings) (8th): It is important we don't just follow the solidworks blindly, because this might lead us to wrong design, so just look at the solidworks for concept and build it from there.

CONCLUDING REMARKS ON RAIL 4 ANALYSIS

From this quick analysis, I conclude that the possession of detailed drawings had a significant effect on Rail 4's discussion. Because of the drawings' detail and completeness, Rail 4 was able to use them as a guide throughout their design and assembly process. As early as day 2, online discussion statements mentioned the design, by way of the drawings, with detail and specificity (2, 9), (2, 11). Because one team member was able to update the drawings with necessary detail to better reflect the emerging physical robot, Rail 4 was able to use drawing updates to modify and finalize the robot assembly. Worth noting is that in the annotated Claw drawings, Rail 4 engaged in a prototyping or tinkering process as did other teams (8, 105). Rail 4's period 8 group was able to create the Claw in one class period, so the Claw design specifics weren't subject to deliberation across class sections. Further, 8th period seemed to receive permission to figure out the Claw for themselves (4, 45).

> (8, 105) (Progress Report, Object, Design Elements) (8th): We were able to start prototyping the claw design structures and decided to use vex parts (more versatile).

> (4, 45) (Design Elements) (8th): I think that we have yet to decide which claw design we will be doing; I just want to leave that up to [D] ('cause he's amazing!

The physical object did receive direct attention from the team members, and it provided important information unavailable in the drawings. On the other hand, it seemed that Rail 4 didn't need to reference the physical object as much as did Rail 1 or Stat 1 in order to communicate their ideas or make claims about the design. Rail 4's design process involved assembling what was drawn and compensating for differences that occurred due to working with physical, three-dimensional components as opposed to two-dimensional representations. This process differs from the one Rail 1 and Stat 1 went though in using the object as its own representation. Rail 4's process had the advantage of efficiency: they completed their robot, and were well on their way to programming it for operation when time ran out.

On the other hand, the existence of detailed drawings does not tell the whole story. The highly detailed drawings were made available by one student of notable experience who also provided clear instructions to the team. As such, Rail 4's design process may have held disadvantages from a learning standpoint. For example, from the timeline it appears that Student D, the creator of the drawings, dominated the design process[31] (see Table 4-4) because the other team members deferred to D's design and instructions. Despite wanting to "work in tandem" (4, 30), period 2 openly deferred to period 8 and D's instructions (5, 59).

> (4, 30) (Team Dynamics) (2nd): The initial design is great, but we just need to both get on the same page so that we know what to do moving forward. Also, if you could let us know of your future design plans it would be great so that we can work in tandem.
>
> (5, 59) (Team Dynamics) (2nd): I feel that my group is better at being instructed that kind of just being creative... so i guess it would help us if y'all would tell us what you want us to do (like [D's] comment above). But if thats too much to ask for then we will work harder on that.

Period 2 had a practical reason for their deference to period 8. TAKS testing drew most of their group out of class for the better part of the build, so following the lead from period 8 seemed like a reasonable option for achieving success in the design challenge. However, the team dynamic across the two periods became clear: all the team members from both periods were essentially following D's instructions, assembling the robot accordingly, and offering feedback and making adjustments from troubleshooting along the way. Perhaps because of the drawings or because of the skill and expertise of student D, the other members of Rail 4 appeared to have low agency in creating and crafting their design. To be fair, I was able only rarely and briefly to observe this team in class. It could be the case the members of period 8 (D's period) had shared responsibility in the design, and it was merely the case that D created the CAD for it. Still, the online discussion did not reveal much agency in the design from across the two periods.

Team Rail 4 provides an example in which the presence of detailed drawings or a student with significantly more design experience contributed to an environment more akin to following instructions than creative engineering design. Interaction with the physical object was necessary to resolve issues not addressed by the drawings; however, the physical object appeared to play a less crucial role in important design decisions.

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[31] To be fair, student D did not dominate the discussion by force of will or personality. D's leadership status was largely granted by the rest of the team.

Chapter 4 Review

To wrap up Chapter 4, I will 1) provide a very brief summary of what was going on within the three teams I analyzed, and 2) describe how this analysis has addressed my original three research questions.

The first step in my analysis scheme was to read the student teams' online discussions in full. At this step I was faced with a very complex problem that presented itself with many inputs and incomplete information. So I did what any designer would do: I apprehended the problem intuitively. After a couple of readings of each complete discussion, I was able to surmise what was going on within each of the three teams. Here are my intuitive assessments, which, in my opinion, still hold up in the face of more thorough analysis.

RAIL 1

The design of period 3 was adopted as a starting point for the team's design right away, and period 5's proposal was for all intents and purposes discarded. The proposal of period 3 seemed like a better idea, and it included some CAD images. The team's overall dilemma was a matter of mismatched expectations. Period 3's understanding of their own design didn't go much further than what they had explained in their proposal, and period 3 wanted help from period 5 to figure out how the various pieces would fit together and how to actually assemble them. Period 5 wanted better explanations from period 3 or some specific instructions to understand period 3's design well enough to contribute to it. Period 3 was unable to provide the desired explanation or instruction because they weren't all that sure of their design themselves. In short, period 5 wanted information period 3 was unable to provide, and period 3 wanted design input that period 5 was unable to give.

Rail 1 fumbled along in this quandary for several days until the design was sufficiently assembled (a foam board House and a good deal of the Arm) that through these objects, both period 3 and period 5 could at last understand the design as a whole. During the early days before the prototypes, period 5 felt marginalized and grew tired of period 3's uninformed delegations. Once the prototypes were built, progress renewed and ruffled feathers were smoothed. By the end, Rail 1 created a truly elegant design.

Stat 1

Stat 1 team members were at odds almost from the beginning. Periods 3 and 5 seemed to be making agreements, but actually they were talking across each other. The team was faced with two viable, yet incompatible, design ideas. Basically, period 3 wanted a shooter on top of a rotating base, and period 5 wanted two fixed shooters with no rotation. However, the difference of opinion was not cleanly divided between periods. For most of the discussion, various team members repeatedly mentioned (in the online discussion) that difference of opinion, but they were unable to resolve it. Many questions went unanswered, and frustration grew because both the third-period and the fifth-period subsets of the team felt like they were not really putting their heads together.

Throughout most of the discussion, each class period was working toward their own vision of the design (rotating or fixed), building parts that could potentially be used for either. Stat 1 could not decide which design to pursue, so their implicit strategy was to delay the decision and build parts that they hoped be compatible with either. This strategy proved almost disastrous. Tensions between class periods grew high; things were said, and they nearly gave up. However, apologies were made, and an eleventh-hour executive decision was made to drastically simplify their design and use what parts they had already assembled in order to create *something* that had a chance of functioning. It took three team members working after school to accomplish that.

Rail 4

Rail 4 had a ringer. One student on the team had more knowledge and experience with robotics and CAD than did any other student in all four sections of the Robotics I class. Even though that student was not forceful, all of the other students quickly deferred to his experience. This deference seemed natural to me. They all wanted to create a winning robot, they all wanted to complete the challenge, and they all wanted a good grade in the class. Why not go with the best design available? Period 2 did not have the ringer in their section, and they advocated for their own design ideas in the early days of the online discussion. However, period 2 had a significant managerial concern: TAKS testing kept taking most of their group out of class. With most of the group absent, period 2 was not able to develop their own ideas to a point where they could be adopted into the overall design. Hence, period 2 adopted the design of period 8, and helped by assembling the robot according to the drawings.

Rail 4 seemed to have a very different experience from the other two teams. The difference is explained by three contributing factors: a highly experienced team member, detailed drawings, and one class period whose members were frequently absent. I only observed Rail 4 on a few occasions, and those encounters were brief. Mostly what I saw were students assembling the robot according to the drawings while making small troubleshooting decisions along the way. Most of what I know about this team's experience is what I read in their online discussion. The differences that emerged raise concerns about the value and use of design drawings, the impact of widely dissimilar experience levels across team members, and the need for team members to be present most of the time.

Section 5: Research Questions Addressed

Finally, here I recap the overall answers to my research questions (without rehashing the arguments I used to justify those results). Here, in brief, are the answers to my original research questions.

1) What characteristics of argumentation emerge from students' design conversations?

Student teams discussed multiple robot subsystems simultaneously, in the sense that on any given class day, the set of online posts for that day (one from each team member) addressed up to five distinct subsystems. In fact, individual students tended to mention more than one subsystem in any given post. The subsystems were certainly interrelated, and so their designs evolved simultaneously; it's worth mentioning, however, that no team sequenced the order of subsystem design or assembly, which suggests that the teams had difficulty prioritizing one subsystem over another. Put another way, the teams were trying to resolve all differences of opinion at the same time.

On average, about 85% of each online discussion was coded by one or more of the following thirteen codes: Design Elements, Drawings, Object, Tasks, Progress Reports, Team Dynamics, Praise, Sperry, Agreement, Questions, Answers, Inviting Ideas, and Inviting Questions. These codes are the types of statements that made up the students' discussions, and thus, their argumentation.

Early on I conjectured that a timeline of the codes for a given team would reveal patterns that indicate when resolutions occurred and what led to those resolutions. Unfortunately, that kind of analysis proved to be tedious, time-consuming, and of course, highly subjective. I was not able to establish distinctive patterns. However, the timelines did provide some insight into the students' discursive and argumentative tendencies, and I elaborated on them in Section 1. Worth noting again is how statements coded Team Dynamics revealed much about how the teams were struggling to resolve their differences. If design teams can expose and discuss such struggles, then argumentation scaffolds may be seen as highly desirable and useful.

Pilot analysis and dissertation analysis both revealed indications of argumentation within the student teams' online discussions. Pilot analysis revealed the use of claims, supported by justifications based on personal experience (e.g., perceptions of how difficult it would be to execute an idea). Subsequent dissertation analysis extended these results by including object-based claims such as visual and tactile inspections of the robot itself. This represents a view of argumentation in which both words and objects combine to form argumentative meaning. Put another way, there were instances when the written argument could only be understood when combined with sensory inspections of the object being addressed.

Important to recognize, however, is the relative weight or effect of their ideas and reasoning (claims and justifications). Reasoning or justification seemed to be more compelling or convincing to other students when that reasoning was tied directly to some physical object (or excellent drawings), namely, a component (or high-quality visual rendering) of the robot itself. Without the support of the object, the students' discussion took the form of argumentation but lacked the substance. Throughout my analysis, I got the impression that the online written discussion was not inducing design progress. Rather, the online discussion worked in concert with, or was a reflection of, a different "discussion" that was taking place between the team members with *the object itself* serving as the primary information vector. The students' argumentation became more collaborative and productive when the students used the object to convey ideas and reasoning that was difficult to articulate in words.

2) How can pragma-dialectic theory be applied to understand the argumentative characteristics of student design discussions?

Even though the use of claims supported by evidence emerged as a characteristic of the students' argumentation (Berland & McKenna, 2010), a claim-evidence cycle alone failed to capture other important characteristics of the design discussions which should be included as part of the argumentation structure. Pragma-dialectic theory states that all argumentation serves the purpose of resolving differences of opinion (van Eemeren and Grootendorst, 2006) and characterizes the resolution process from the point when a difference of opinion is recognized to the point that it is resolved. Thus in design PD theory is potentially relevant and important because designers must not only be able to argue for and defend their ideas, they must be able to select which (differing) ideas are worth discussing. They must be able to determine which differences of opinion are worth resolving and which should be left ambiguous for the sake of making progress (Cross and Cross, 1995; Harrison and Minneman, 1996; Minneman, 1991).

The students in this dissertation study appeared to be resolving differences of opinion on design issues of their own choosing. This was revealed by analyzing the text according to Pragma-dialectic theory; that is, statements within the text could be characterized as being part of the Confrontation, Opening, Argumentation, or Concluding stages. Such categorization was of course subject to the interpretation of one analyst, myself, and should be considered conclusive. However, an argumentation model based on resolving differences of opinion remains promising for an engineering design instructional context.[32] In design, it is entirely possible to have two (or more) competing design opinions which are both well-founded and align with scientific and engineering principles. Nevertheless, a choice must be made. Further, the four PD stages may serve as a beneficial argumentation scaffold for students. Knowing that design discussions involve resolving differences of opinion and that there is a normative guide for doing so (PD theory) may give students (designers) useful awareness around the nature of the discussion at hand. Such knowledge may also help accelerate the design process.

The overall goal in team design is for the team members to convince one another to adopt a single vision of a design "that does the job" while aligning that vision with the physical realities of what they can actually accomplish as a design team. They achieve their ends by resolving competing design visions, which, within the realm of discourse, may be considered opinions. Designers' opinions—ranging from those that are well-supported technically, theoretically, experientially, and practically, to those that are less well-supported matters of preference—are the driving force of design, from identifying the problem to creating a solution. Therefore, PD, as a theory that focuses on the resolution of differences of opinion, is a good candidate for both understanding and supporting the development of design discourse through argumentation.

The online discussions contained evidence suggesting the presences of the four stages of a PD resolution of differences of opinion. Because PD was designed to describe resolution processes in conversations in general, it's not too surprising that one could find the four stages simply by looking for them. After all, PD theory states that they *will*

[32] It may be suitable for professionals as well.

occur. However, that the students passed through the four stages, albeit in a rudimentary way, suggests that PD theory may be suitable as an analytical tool and potentially useful as a normative guide to help students use those stages more productively. I describe one way of doing so in Chapter 5.

3) How do the students use their own tacit knowledge and objects to resolve design challenges, and how does their tacit knowledge relate to their argumentation practices and team design efforts?

Because beginning designers rely on thinking that precedes articulation, and because argumentation *requires* articulation, using argumentation to support the development of beginning designers may require special considerations, namely, leveraging physical objects as both affordances for making arguments and as indicators for when differences of opinion get resolved. In my research, the students' use of tacit knowledge and objects showed up specifically as statements I am classifying as object-based claims: keystone, tinkering, tactile, visual, and counter-factual. They were making arguments about the design and the object which required the presence of that object to convey meaning.

In this way, the object provides a crucial affordance for engaging in—and making useful sense through—argumentation. The object serves to link the tacit knowledge and intuitive thinking among students, and thus creates meaning in arguments that might not otherwise make sense. If students are encouraged to—iteratively, rapidly—instantiate their ideas in physical form, they will have better opportunity to articulate their ideas linguistically and engage in productive argumentation. Frequent reflection may support the development of argumentation skills in students. Already, frequent reflection is known to lead to better designs (Cross, Christiaans, and Dorst, 1994).

As described elsewhere in this dissertation (and particularly in the literature review), tacit knowledge plays an important role in design for many reasons. For example, design is the creation of value through the judicious combination of artifacts and known principles (Dorst, 2011). Understanding and interpreting that value comes from the ways through which human beings interact with the world and with each other, and much of that interaction is tacit. The quality of a design may not always be articulated—it must often be seen, touched, heard, and otherwise experienced in some visceral way. The value of any design—the way a designed object conveys information and meaning—is often understood tacitly (Cross, 1982).

CHAPTER 5: DISCUSSION AND RECOMMENDATIONS

In this final chapter, I will review lessons learned about the role of objects in argumentation and offer what I hope to be a contribution to a theory of object-based argumentation. I will briefly review the lessons learned about the role of designed objects in argumentation, and offer a contribution to a theory of object-based argumentation. Then I will draw from this study, research literature, and my personal experience to make some recommendations to educators particularly in the regards to the instruction of engineering design and the acculturation of students to the world of novice engineers. Last, I will make some suggestions for future research and the development of a theory of object-based argumentation.

Reflections on Results of the Study

CONTRIBUTIONS OF THE STUDY: LITERATURE REVIEW

In this study I explored the potential benefits of using argumentation, as a formal, discursive practice in engineering design instructional settings. The overall concept is that students argue to learn while learning to argue (Andriessen, 2006; Jonassen & Kim, 2010). This appears to work well in science classrooms, and it mirrors the practices of the scientific community. However, engineering designers tend not to refer to *argumentation*, per se, within design contexts. Designers certainly provide rationale for their ideas, but the rigors of argumentation theory are rarely applied. In a design context, students would learn to create better designs by arguing more formally about them, while using engineering design as an information rich context to learn how to formulate (and dispute) convincing arguments. There is still work to do in order to understand how best to apply argumentation within a design context.

My hope is that this dissertation serves as a foundation from which to continue to explore, with greater precision, strategies for leveraging argumentation theory with an engineering design instructional context. I explored that question in two ways: a literature review that reached into various fields not commonly included in engineering education articles and a discourse analysis of novice designers in a high school robotics class. I examined literature from the following fields:

design (broadly defined and beyond engineering) to gain a broader perspective on how humans go about designing things and why; to challenge the old ideas that engineering science means the “fundamental knowledge of the laws of nature which permit the mastery of the resources and powers of nature” (Kline, 2000, p. 20) or that engineering is "the art of the economic application of science to social purposes (Waterman, 1952, p. 641).

cognitive psychology (specifically, implicit learning, intuition and analysis in problem-solving, tacit knowledge, and knowledge articulation) to better support my scholastic discovery that design is a kind of problem-solving which combines intuitive and analytical thinking, tacit and explicit knowledge;

argumentation theory (Pragma-dialectics, an argument structure for resolving differences of opinion) in order to apply some framework for my own discourse analysis and to posit an initial argumentation theory for design—one that can serve as both analytical tool and normative guide, one that values arguments that serve resolution and consensus-building, one that allows the discussants (e.g., design team members) to determine for themselves what makes an argument convincing;

argumentation practice (lessons learned in science classrooms) in order to describe some of the strengths and challenges of using argumentation as pedagogy in classrooms.

While writing this review I learned that engineering design is about a lot more than the application of mathematics and science. Design is a way of solving problems, a way that is powerful, human, iterative, heavily reliant on personal experience, perspective, and intuition. It is a way of resolving competing requirements to create new value (Dorst, 2011). Design is becoming more and more a team effort that requires communicating clearly, resolving disagreements, and understanding problems through multiple perspectives. As such, design courses, including robotics, may prove ideal settings for students to practice working with different perspectives and resolving competing ideas within a team, using specific discursive techniques like argumentation.

Further, design courses, including robotics, may be attractive to a broad range of students in high school. Within such courses, students can learn how assess a situation, and design creative solutions which add value to the situation where once there was a problem. Doing so involves a range of abilities not the least of which is the ability to work collaboratively and productively within a team. For example, students can learn to recognize the differences and interactions between task and relationship conflicts (Jehn, 1995), and how to proceed once the occur. (Note: such conflicts may be considered differences of opinion for which Pragma-dialectic theory may provide strategies for resolution.) Team work encompasses knowledge, skills, and abilities that can benefit all students regardless of career path. Herein lies the real juice of design courses, which I believe should be foregrounded and brought into focus.

There is much research on team dynamics and collaboration within the realms of Administrative Science and Organizational Management, for examples, which I did not address. The literature review of this study is a step into a broader conceptualization of design (e.g. engineering design) that can inform the creation of high school design courses. Further examinations of multiple literature bases should expand upon the review of this dissertation.

Questions remain regarding the motivation for teaching design, particularly engineering design, in secondary schools: What students do we wish to attract? What kinds of experiences do we want these students to have? What do we want them to learn? To guide my future work in this area, I have created my own characterization of engineering design. Rather than an artful or economic application of science and mathematics, I see engineering design as a subset of design—a subset that maximizes the use of scientific and mathematical principles. A subtle difference, but one I think valuable for the future of education.

CONTRIBUTIONS OF THE STUDY: CLOSE EXAMINATION

This dissertation study is limited by its single setting. Repeating this study, or iterations thereof, in multiple settings would be useful; however, reserving my conclusions while awaiting reproducible results belies the power of close observation and analysis of a single setting. Consider, most of the design studies I referenced were protocol analysis of small design teams in a laboratory setting. Likewise, studies on the use of intuition in problem solving took place in contrived settings. The problems presented to the study participants were authentic, but the environments were facsimile. Results of these lab studies greatly informed my work and continue to move the research forward.

Some studies, by Bucciarelli or Hutchins, to mention a couple, were more ethnographic and took place in authentic work environments. As such, they are insightful, but difficult to conduct. My study, I believe, has an advantage of ecological validity because it took place in a classroom with real students, real grades, etc. Apart from a couple of notable features (i.e., online communication, and a novel design challenge), the robotics classroom setting for this study was comparable to other robotics classes engaged in a robotics competition. The pedagogical structures Mr. Sperry and I applied over the course of the semester were reflective of current common practices. So in a sense, this study was a close inspection of how students responded to a semester long robotics competition challenge.

The nature of robotics classrooms was not the focus of my research questions, per se. For me the setting was an appropriate vehicle by which to examine student use of argumentation and physical objects. Still, close examination of this setting has provided some insights that could support future research, and improved teaching practice in both robotics and engineering design more broadly. For example,

a) Students wanted to resolve differences and develop team cohesion around a single design; they wanted buy-in from all team members. Ideas were not dismissed out of hand, and students were not attacked personally (ad hominem fallacy) in order to usurp their positions.

b) Team Dynamics codes were particularly insightful. They were forthcoming about their judgments of one another's words and actions and their frustrations with team interactions. Through these coded statements, I can see potential for examining these teams' discussions from the perspective of "task" or "relationship" conflicts (Jehn, 1995) to see how the two kinds of conflicts get resolved. At this point, I can speculate that when task conflicts lingered unresolved, they developed into relationship conflicts. Rail 1 seemed to come together once the task was clearly understood by nearly all of the team members. Stat 1 appeared to patch up their relationships first, and then moved toward the task at hand. Also, because Rail 4 was essentially following the leader, there were no significant relationship conflicts.

This result can lead to questions about the role of argumentation in team conflict resolution, and how research from other fields may be applied to engineering design instructional settings.

c) Design through online interactions is possible in a high school setting. The students here did not like it, but they also recognized it as an instructive experience. They realized that the online communication portion of the challenge was a genuine, if problematic, attempt to give them an authentic, professional engineering experience. There is certainly room for improvement. STEM classes have recently been experimenting with blogs, wikis, discussion boards, etc. CSCW and CSCL researchers have been studying online interactions for years. How can lessons from STEM classes or the CSCW/L literature be applied to support online student design interactions?

d) There are important questions about argumentation that this study could not address. For instance, it's known that frequent reflection periods increase design outcomes (cf. Cross, Christiaans, and Dorst, 1994). How can argumentation practices support interactions within those reflection periods? How might a transcript of prior online discussion support better reflection and argumentation therein?

e) A problem with robotics challenges is that the designs are necessarily complex; therefore, it takes students a long time to build something that they can test—something they can reflect upon. How can students optimize periods of reflection when their design is incomplete, even rudimentary?

f) How do argumentation patterns change from periods of creation and construction to periods of reflection and analysis? Given the time required to assemble (and program) a working robot, periods of reflection may be few and far between. How can design challenges be structured so that periods of reflection can occur frequently and be meaningful to the students?

I could not have made the above observations, a) through f) without the benefit of close student observation and careful analysis of their online discussions. Further, it was through qualitative approach to this study that I have been able to formulate more specific and, hopefully, more insightful questions for further research.

ARGUMENTATION AND THE DESIGNED OBJECT

This dissertation study has been an attempt to understand the role argumentation plays in an engineering design context. Specifically, I examined the online discussions of students in their first year of an engineering design course: high school students in a first year robotics course. I supposed that if one wishes to use argumentation to support the development of engineering design students, then it would be helpful to have some understanding of how beginning students used argumentation naturally, without explicit training therein. That way educators could design argumentation scaffolds that would enhance the students' existing discursive strengths while ameliorating their weaknesses. Of course creating scaffolds based upon one study means recognizing that any conclusions of that study would be limited and better supported through subsequent research. However, combined with the support of relevant research in design, argumentation, and cognitive psychology, I believe that the results of this study may be informative.

Over all the biggest result had to do with the role of physical objects within the students' deliberations, in particular the role of the physical instantiations of their design ideas. When novices take on a complex engineering design challenge, they tend to rely on intuition in order to make sense of the challenge and begin to devise design solutions. Relying on intuition in the face of complexity is natural and can produce good solutions

(See Chapter 2 for details). In doing so, students are relying on a kind of knowledge (i.e., tacit knowledge) that precedes articulation. In fact once articulated, the knowledge is no longer tacit, and it loses some of its intuitive force. The problem is that communicating tacit knowledge with a design team member, for example, for the purpose of productive collaboration is difficult.[33] Supporting the communication of novice designers—those relying on intuition—is a challenge.

Argumentation strategies have been employed to support even young students' communication in science and other fields with some success. However, argumentation can only begin once knowledge has been articulated. So, the question arises, how might argumentation support the communication of knowledge that is pre-articulation or tacit? Part of the answer, at least for engineering design scenarios, may lie within the designed physical object. If we consider an argument to be something that holds meaning as a combination of words and physical objects, then we can leverage argumentation theory to support the communication of both articulated knowledge and tacit knowledge. It has long been known among designers that objects convey tacit knowledge (cf. Abel, 1982; Cross, 1982),[34] and argumentation has a long history of supporting communication. There is much work to be done in this area, but argumentation may be developed for use as a communication scaffold in engineering design where objects are used extensively and conveying tacit knowledge is often essential.

Important to keep in mind is that in engineering design, objects are not merely affordances for communication, they are themselves the goal of that communication, indeed, of the entire design process. This dual role of objects[35] should be considered carefully and examined in more situations, especially instructional environments. One contribution to the use of argumentation in engineering design is the three categories of Object Claims I defined in Chapter 4. Definitions for which are as follows:

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[33] In fact, researchers are currently working on this problem (Kreiner, 2002; Lam, 2000; Mareis, 2012; McAdam, Mason, & McCrory, 2007; Schmidt, 2012).

[34] This is also the focus of boundary object theory (Star & Griesemer, 1989; Star, 2010).

[35] In Activity Theory, the object also serves a dual role as "objekt"—a physical entity, and as "predmet"—a physical entity as it relates to certain human intentions (Kaptelinin, 2012). An object-based theory of argumentation ought to be informed by Activity Theory. It was my original intention to use Activity Theory as an over-arching framework, but it became too unwieldy for a single dissertation.

Establishment Claims: assertions that an intermediate design step has been or should be established.

- *Keystone object claims*: assertions that something is a preferred intermediate step towards the completion of the design as a whole.
- *Tinkering object claims*: linguistic markers for process(es) through which a *keystone* is developed—or through which other design components are developed, possibly with respect to the *keystone*.

Constraint Claims identify physical realities or observations about the environment that articulate the constraints—the things that must be attended to—in the development of a keystone, possibly through tinkering

- *Tactile constraint claims*: identify physical realities or environmental observations that must be perceived through touch.
- *Visual constraint claims*: identify physical realities or environmental observations that must be perceived by sight.

Counterfactual Claims: propose the establishment of some design idea or modification ("then") that can occur once certain constraints are met ("if")

- May serve as both establishment and constraint claims

I consider these categories to be part of an argumentation structure that supports resolving differences of opinion in which physical objects play a crucial role. These *Object Claims* might be used within a coding scheme for discourse analysis or as components of a communication scaffold for engineering design students.

PREFENTIAL TREATMENT OF THE OBJECT

In the analysis chapter, I emphasized use of the designed physical object as an information vector to promote clear communication and productive collaboration. Later in chapter 5, I will recommend that design educators devise iterative design challenges and emphasize rapid prototyping. Doing so allows students to generate concrete objects quickly as anchors for design discussions. Although I believe these strategies will prove effective, they could backfire. One could ask if the objects themselves might deter from students' articulation of ideas, or if a working design is the end-game, then students need not think more deeply about their designs than is necessary to produce something functional. This is a fair question, especially considering students' tendency to dodge the application of math and science principles to their designs in favor of more trial and error methods (Berland, 2013). In other words, why struggle to articulate complex ideas when an object can carry the necessary information?

From the literature on design, I can say there is a balance to strike within design discourse. On the one hand, objects and artifacts are essential components of design discussions (Bucciarelli, 1994, 2002; Cross, Christiaans, & Dorst, 1996; Henderson, 2000; see also Chapter 2 of this document). Design artifacts carry critical information in non-verbal modes of communication. Learning to incorporate artifacts into design discussions in such a way that promotes clear communication is vital when learning to design. On the other hand, there is important information not carried by artifacts that must be articulated. For instance, designers rely on implicit, cultural knowledge of the physical objects which supports using representations, like drawings, more effectively (Leonardi & Bailey, 2008). Learning how to strike a discursive balance between object-based information and words takes expereince, and professional circumstances often provide the inpetus to focus more on verbal or written communication.

Thus, in various design courses, students may require incentives to articulate their ideas in words. For instance, *necessary* online interactions with members of a design team certainly requires more articulation (in writing) than face to face conversations. It may also be the case that online articulation gets enhanced by the presence of a physical object that is shared by the design team members. Within the discussions analyzed in this dissertation, the presence of an object did not dilute the students' use of language. Rather, the object's presence seemed to increase linguistic specificity and conceptual depth. Once the design ideas became sufficiently instantiated in physical form, the students began to discuss those designs in greater detail with more comprehensive understanding. Consider student statements a. through n., pp. 119-122 of this document. Statements a. to f. occurred prior to the creation of the House prototype; whereas, statements g. to n. occurred after. In the later statements, the students were able to refer to specific robotics parts by name perhaps because the physical form of the design allowed them to discern which specific parts would be suitable. Also, the conceptual reasons behind the use of

Lexan for the House (as opposed to metal parts) came into focus. Previously, that understanding had been unresolved. Even though the object was carrying information the students did not (and perhaps, could not) articulate, the students were able to discuss that information more clearly.

In this study, the students' ability to articulate and convey their ideas may show up within their object-based claims. A worthwhile exercise for future publication might be to qualify the students' object-based claims based on specificity and epression of understanding. Does object-based claim quality increase with the formation of the designed physical object?

Another incentive for articulation might include the production of reports about the design. In laboratories, engineered products are tested for a variety of properties, e.g., acoustic, thermal, load stress, weather resistance, etc. In such lab reports, the engineered product must be described, in words, in great detail.[36] Report writing, as a classroom exercise, may not be as enticing as design work with a remote team, but it is an authentic and necessary practice of engineers. Based on this dissertation, which included reading the students' design proposals, I suspect that writing detailed descriptions of designs the students had already built would greatly help them describe what they will design next. (Again, writing detailed reports was part of the original design challenge plan for the students, but we ran out of time.)

I maintian that engineering design students should create physical objects early and often throughout the design process. From personal experience, the literature on design and engineering, and results from this study imply that having a physical object available for discussion is incredibly valuable. Further, I suspect that emerging complexity of the designed object will coincide with emerging complexity of the students' discussions.

[36] In my time as a novice lab engineering, this was a substantial, but ultimately beneficial, challenge.

Recommendations to Educators

Recommendations Regarding the Creation and Implementation of Design Challenges

1. Create iterative design challenges, beginning with ones solvable through tinkering or trial and error, moving towards those that require analysis and the incorporation of scientific or mathematical principles.

Approaching challenges that are iterative, that is, with increasing levels of complexity, supports instruction that nurtures both intuitive and analytical thinking. Both have been deemed essential for design thinking, and both deserve attention in a learning environment. In design, the use of intuition or tacit knowledge to arrive at solutions is common among novices and experts alike. In fact, the ability to fluidly and effectively balance intuitive and analytical thinking as appropriate to the task is a definitive mark of expertise in design. Novices tend to rely more upon intuitive problem solving approaches, whereas experts can readily incorporate analytical strategies in concert with intuitive strategies. The choice of one strategy over another (or the choice to employ a combination) is influenced by the nature of the problem itself. In situations that include many complex inputs or absent or incomplete information, an intuitive strategy can be highly successful in generating satisfactory solutions. In situations where inputs are simple or the information is complete, an analytical strategy can be highly effective. Unlike novices, experts have the ability to sift through complex or incomplete information and pick out the key pieces of information present and identify the remaining information that needs to be determined. Thus experts have the ability to apprehend a complex problem intuitively while searching for specific information to support analysis.

Design problems often present themselves through complex inputs, that is, multiple sources of various kinds of information, that can be mined for critical components. The complexity intrinsic to real-world design problems is why expert designers balance the use of intuitive and analytical thinking. Thinking about design analytically, however, requires practice, theoretical knowledge, and a sufficiently broad base of experience. Thus, analytical thinking in design requires time to develop. It is also the case that novice designers are able to design satisfactory solutions to appropriately chosen challenges without the benefit of analytical thinking, as evidenced in the research literature, this dissertation, and my observations of other novice designers in high school.

Specifically, in this dissertation, I showed that though the two teams under study engaged in argumentation, some members of each team did not seem to understand those arguments until those members developed some tacit understanding of the designed objects at hand. For these students, designing and building their solutions was a process based largely on tacit knowledge and intuitive thinking. Argumentation, on the other hand, relies on the presence of explicit knowledge—and is a mode of reasoning that is more analytical than intuitive. For these students, argumentation did not become useful until they had explicated their knowledge of their design, a process they conducted through the reification of design ideas into a physical object. By accessing the design challenge's physical objects—via visual and tactile inspection—they were able to explicate, and therefore discuss, specific, critical pieces of information.

The students made keystone and tinkering claims to which they were able to apply meaningful constraints (tactile and visual claims) once a shared design object became accessible. These students demonstrated that they were able to think analytically, in the form of argumentation, about their designs after their intuitive design strategies enabled them to extract key pieces of information that could be mutually understood and discussed.

When creating design challenges, it is tempting to craft them in such a way as to require the use of mathematical or scientific principles. Such challenges have been created and implemented in high school classrooms of design novices, yet results suggest that the students made little use of math or science in their design process (Berland, 2013; Silk & Schuun, 2008). I suggest that this situation is not a problem, per se. I propose that as a counterbalance to the historical emphasis on explicit analysis in engineering education (cf. Dym, 2005; Farrell & Hooker, 2013; Galle & Kroes, 2014; Kline, 2000; Silk & Schuun, 2008; Waterman, 1952), STEM educators—or, at the very least, instructors of novice engineers—infuse STEM pedagogy with a healthy respect for the value of tinkering (that is, intuitive trial-and-error experimentation) as a legitimate, and, I argue, crucial aspect of acculturating novice engineers.

Based on my research and observations, introductory design courses should focus on the acculturation of students to a community of novice engineering designers. This means providing opportunities and timely feedback in order for students to develop intuitive thinking abilities and incorporate the tacit knowledge critical for design practice. Introductory classes may also provide a good opportunity for students to begin to learn how to convey complex ideas and to negotiate competing complex ideas with and among their colleagues. The communication difficulties students encounter may prime them for the introduction of specific argumentative techniques used in resolving differences of opinion.

1A. EXAMPLES OF ITERATIVE DESIGN CHALLENGES

One way to iterate design challenges is to build upon a theme. An instructor can choose a set of engineering principles that are common and tend to occur together. For example, in Table 5-1, the centrifuge example (1 and 1A) deals with rotational velocity and acceleration, balance, and gear ratios. The lift example (2 and 2A) deals with mechanical advantage during lift and can include a wide variety of such systems. Example 3 and 3A deals more with a recurring engineering problem, i.e., controlling vehicular motion, than with a set of principles, per se. Exploring recurring problems that have a wide variety of possible solutions is another way to create iterative design challenges.

1) Build a centrifuge. This task involves one of a number of mechanical techniques for high-speed rotation. The students can explore those techniques.	1A) Build a centrifuge that can handle one or more vials and be able separate a mixture without damaging the contents. Now the students must contend with compensating for an off-balance system and consider achieving a specific rotational velocity within certain tolerance limits. Acceleration and deceleration may also be factors.
2) Build a device that can lift 5lbs one foot. This is not particularly difficult with common robotics components, and it can be done in many different ways (e.g., a crane, a front loader, a forklift, etc.)	2A) Build a device that can lift 25lbs (or some appropriate, but heavy weight) one foot. Even simple motions become much more complex when the object is heavy. Starting from the designs from the first iteration, round two could involve a variety of load and stress calculations. For example, the load can simply be more than a kit motor can lift unassisted.
3) Build a robot that can follow a painted line on the floor. This is a common challenge in robotics classes. It requires the design and integration of a vehicle (wheels, tank treads, legs, etc.), one or more sensors, and a program. Although the vehicle design and the program are relatively straightforward, synchronizing the two typically requires some tinkering and running trials to observe how programming or mechanical modifications perform on the track.	3A) Follow the painted line without spilling some liquid cargo. The additional requirement requires understanding of fluid dynamics, and the ability to deal with acceleration and sudden changes in direction. It also provides opportunity to inform programming and mechanical adjustments through simulations and experiments.

Table 5-1: Design Challenge Sequences

Within an iterative design progression, timing is critical for an instructor. It's likely that student teams will progress at their own pace, and knowing when to promote tinkering (i.e., intuitive thinking) or when to encourage more analysis is hard to prescribe. It's important to be able to add design constraints as the student or student team becomes ready for them. One way to support good instructional timing is to incorporate frequent opportunities for design reflection. During reflection students discuss the current state of their design, identify strengths and weaknesses, and make plans. Reflection times also provide the instructor with opportunities to listen to his students and provide feedback.

Frequent opportunities for reflection gives students many opportunities to practice argumentation techniques, which in turn, may help to make the reflection times more efficient. Reflection times are also a window of opportunity for instructors to gauge their students' thinking and provide timely feedback. The patterns within the students' discussions, i.e., argumentation patterns, can provide important clues to the instructor. Argumentation is a linguistic mode of analytical thinking, and how the students argue about their design ideas may indicate their readiness for greater complexity and the incorporation of other forms of analysis (e.g., scientific, mathematical, engineering). One way to encourage frequent reflection is through rapid prototyping.

2. Consider design challenges that lend themselves to rapid prototyping and provide the necessary materials.

I found that the students' conversations became much more specific and productive once they had a common physical object to reference. A prototype *could* be a drawing, but a physical, three-dimensional object seemed to hold advantages over a drawing, such as providing a basis for making *tactile* claims. As novices, the students' ability to generate and work with mental representations of their design is limited, as is their ability to communicate about those representations. The existence of a physical object enables direct visual and tactile inspection, which, in turn, seemed to increase the students' ability to understand one another's comments and to engage in more collaborative argumentation. A physical object also represents a reification of a complex mental web of design decisions and alternatives. Once reified, previous ideas are in a sense stored in the object. From there the students can engage in counterfactual exercises (if…then scenarios) regarding new possibilities.

Research on design suggests that for novices, spending large amounts of time scoping the problem (conceiving possibilities, gathering information) does not necessarily lead to better designs (Cross, 2004). Novices tend to produce better designs if they generate a small set of options; choose one, and act on it (or, for robotics, build it). On the other hand, spending time reflecting on the design in progress does lead to better designs, even for novices (Cross, Cristiaans, and Dorst, 1994). As my dissertation research suggests, students need an object upon which to reflect, and reflection allows for more collaborative argumentation. Therefore, generating physical mockups early should prove efficacious and instructional. Again, these mock-ups provide opportunities for the instructor to witness the development of the students' tacit knowledge and give feedback in a constructive and timely manner.

Regarding feedback, design instructors should be aware of 'satisficing'—the tendency to patch or modify existing design solutions to overcome unforeseen obstacles. Even expert designers have the tendency to get locked in to a design solution and satisfice that solution towards a successful outcome rather than beginning anew with a different (possibly better) solution. The value of satisficing as a design strategy remains an open question, but it does occur, and instructors should be aware of this tendency.

Students can create prototypes out of many kinds of materials, and the value of disposable material like paper, cardboard, poster board, plastic, aluminum foil, tape, glue, and various refuse should not be underestimated. Such material is at most cheap, and is often available free for the asking from local businesses, shops, etc.[37] Encourage students to build rough mock-ups of their design ideas quickly; it gives them something concrete to talk about. Design is a compromise between what one can envision and what one can actually make. For novices especially, envisioning and making should go hand-in-hand.

3. Decide beforehand if the students will make design drawings, and if so, whether they will use paper or electronic drawings.

The students in my study had a difficult time creating useful CAD drawings. Difficulty in learning the software notwithstanding, all of the class periods lost their nearly complete drawings to a server crash. Even without this major technical setback, their CAD drawings were not of high quality, which is of course understandable; learning CAD software can be a semester-long engagement unto itself. Whether and in what capacity first-year robotics students should use CAD software is an open question. What

[37] Dumpster diving, I'm told, yields great rewards.

is certain is that these students wanted to use their drawings, as evidenced by my coding of their online discussions. The students also lamented the lack of utility of the drawings they did have, or the absence of the drawings altogether.

Hence, if an instructor wishes for the students to use drawings to support the design process—as a shared common artifact upon which to reflect, for example—he or she may consider choosing a medium in which the students can create useful drawings. CAD is not inherently better than paper when first learning to design. As I learned by examining the discussions of Rail 4, the use of drawings could backfire. If, for example, the drawings are created by a single individual or are exceptionally detailed, the design process could devolve to following instructions. It may be the case that drawings deprive students from having valuable learning experiences by way of visual and tactile explorations of the actual object. Among professional engineers, drawings are used as tools to communicate and adjust ideas prior to manufacture, which could be costly (i.e. in materials, money, time). In robotics class there is little cost to assembling and disassembling parts while tinkering and fleshing out ideas, and such experiences could be particularly valuable to students. The use of drawings in introductory design presents affordances and liabilities, and the instructor should consider these carefully when preparing for the course.

4. Asynchronous design holds advantages for students in a high school setting.

Asynchronous design offers students participation in an acculturative practice commensurate with those of modern engineering professionals. Product design often involves participants from multiple departments on a single campus in which frequent face-to-face communication isn't plausible. In this case, the design process is spatially distributed. Even though personnel may be working at the same time, they are spread out, use electronic communication, and share possession of the designed objects they are working with. In some cases design engineers are separated by time zones. This is referred to as temporally distributed design. In this case, face-to-face communication may be impossible at any time, but is at least very rare. Temporally, and often consequently spatially, distributed designers have the added challenge of delayed communication. Thus, reliance on quick responses to questions can't be integral to any design communication strategy.

The setting of this dissertation study was an approximation of spatially and temporally distributed design settings. The students all did their work in the same classroom, with the same object, materials, and tools, but at different times. Communication response time ranged from a few hours to overnight. Essentially, this classroom setting allowed the students to view and examine the same object, but removed communicative affordances like pointing and making demonstrations with objects. These restrictions required the students to articulate their ideas, descriptions, concerns, etc., more than would be necessary when communicating face-to-face. Even this approximation setting was challenging for the students; however, they engaged, and the experience seemed to be worthwhile.

In order for asynchronous design to work successfully, a few conditions should be met. The conditions are similar to creating a need to know in the students. Specifically, if team A and team B are to work collaboratively, both A and B must believe that contributions from the other team are necessary in order to complete the challenge. Communicating design information online is difficult. Modeling, gestures, and facial expressions are eliminated; for novices working from tacit knowledge, these communication techniques are valuable. In order to be willing to overcome those difficulties, students must realize that electronic communication is worthwhile.

One way to help establish that asynchronous design is worthwhile is to devise a design challenge worthy of the efforts of two separate teams. In other words, more work than four students, for example, could accomplish themselves. Mr. Sperry and I attempted to create a challenge at this level by including tasks beyond the build stage that included the students performing tests on their designs and writing test reports. Unfortunately, no team reached this stage, but the presentation of workload helped them believe that eight students would be necessary. Another way to motivate asynchronous design is to directly explain the importance of gaining experience working in such an environment (Paretti, 2008). It has been my—and Mr. Sperry's—experience in working with these and other students that they know a contrived classroom assignment when they see one. On the other hand, they were willing to engage in difficult, even ornery, assignments if they believed that their participation held genuine educational or professional value.

This dissertation exercise also provided me with some insights on how to better facilitate asynchronous design. For example, ensure that students can share images electronically. For these students, sharing images through Google docs proved unfeasible; however, multiple teams expressed a desire to do so. Using Google docs held advantages and disadvantages, including that the requirement to communicate only through Google docs eliminated email, text, phone calls, instant messaging, video conferencing, etc., that the students may have used without the imposed restriction. An instructor should consider allowing such communication as it may prove useful to the students and is common in asynchronous working environments; however, such communication modes are difficult to track. For research purposes, tracking the teams' entire online discussion was essential, but if not conducting research, this requirement may be dropped. On the other hand, a record of a team's discussion could be used by the team as a common artifact upon which to reflect regarding their design and resolution processes. Examination of the communication record could scaffold a reflection process that includes identifying and articulating specific differences of opinion, how resolution occurred, and what arguments were convincing (or not). The record could also be opened for review by other teams or instructors. Facilitating asynchronous design for high school students requires planning and balancing affordances and liabilities, but it can be done. It also, in my opinion, can be worthwhile.

5. Consider teaching argumentation practices directly and/or establishing classroom norms that embody the spirit of argumentation.

Although direct teaching of argumentation strategies has been shown to be effective (see Cavagnetto, 2010, for review), students will likely benefit from feeling for themselves a genuine need to use such strategies. Again, timing is important. Consider providing some time for students to discuss their design ideas as best their conversation skills allow. Then, perhaps after a touch of frustration has set in, show them a better way—that there are techniques they can learn which will make their discussions more effective and potentially less stressful.

When considering argumentation as a scaffold for learning engineering design in teams, the following might be considered.

1) The designers' discussions may be broadly framed as the resolution of differences of opinion, of which argumentation is but one part. A primary goal of design deliberations is consensus towards supporting the design process. Consensus can mean an alignment of ideas or an agreement to leave things ambiguous for the sake of expediency (Cross and Cross, 1996). So the design discussion should be viewed holistically, from the point at which the designers (as discussants) recognize that a difference of opinion exists to the point at which the difference is resolved. Within a design discussion, there are multiple points of disagreement, and each should be considered individually and in relation to other disagreements at play.
2) The designed object is the primary object whose gravitational force shapes the entire design discussion and the argumentation therein. For students just beginning their acculturation to the world of novice engineering design, the object will serve both as an affordance for argumentation—the vector that conveys information necessary for argumentation to occur—and as the physical instantiation of the resolutions that occurred a result of deliberation—the physical "proof" that the students resolved their differences of opinion.
3) Argumentation related to design manifested itself in five linguistic categories I am calling *Object Claims*. The five claims are *keystone, tinkering, visual, tactile,* and *counterfactual.* These terms are defined in Chapter 4, and were developed through research of relevant literature and analysis of student robotics design work. The list of five terms may not be complete. For example, aural and olfactory claims did not appear in my data, but certainly could have given the proper circumstance. The list, however, does provide educators with a set of observable linguistic categories with which to monitor and scaffold student design discourse.
4) In crafting arguments related to engineering design work, it's important that students (within a design team) should determine for themselves what sorts of arguments are convincing to their peers. Beginning designers will be solving design problems primarily based on their own intuition, and it is psychologically valuable to nurture that intuition by resolving differences of opinion and crafting a working design based on their existing knowledge and know-how. Nurturing

design intuition occurs more readily in "kind environments" (Hogarth, 2002; Pretz, 2008) where feedback (from teachers, mentors, peers) is timely, constructive, and attuned to the particulars of the immediate environment.

5a. Implementing Pragma-Dialectics

In developing argumentation scaffolds, I believe educators might consider that students could benefit by having some awareness that during their design deliberations they are engaging in the resolution of differences of opinion. Teaching certain principles of pragma-dialectic theory directly may help foster that awareness. Of course, pedagogical timing is important. Techniques for resolving differences of opinion would be of better use when the students have a difference of opinion they *want* to resolve. The principles I am considering here include knowledge of the four stages of a critical discussion according to PD. Teaching the students characteristics of the stages in a way that is relevant to design may help the students to use the stages productively. Based on my research, I have characterized the four PD stages as they might be used in working with novice engineering students.

1. *Confrontation Stage*—Students should recognize that differences of opinion will occur and that they should endeavor to articulate those differences as precisely as possible. Students list competing ideas (differences that need to be resolved) and pay attention to the list.
2. *Opening Stage*—Find *some* common agreement (shared knowledge, shared opinions, a design choice) between competing ideas and build upon it quickly. Begin to determine how that common agreement will need to be refined in order to make the design functional and its performance measurable.
3. *Argumentation Stage*—In this stage, students will begin to become more specific about what is necessary to achieve functionality. They will also learn important design details (tacitly, perhaps) that will inform the quality of the agreement made in the opening stage. Arguments may lead to a new confrontation or opening stage in which they make a revised or different design choice.

4. *Concluding Stage*—Resolutions during the design process may range in magnitude. They may result in relatively small modifications to an idea or the designed object after very little discussion. Resolutions may also represent more significant agreements after prolonged and potentially heated discussion. What is important to realize is that the resolution process happens iteratively and incorporates small-to-large design issues.

Also based on my research, I further note that throughout all four pragma-dialectical stages, the object, in various levels of completion, will play a central role in the students' deliberations. The students may be encouraged to recognize this likelihood and generate designed objects quickly. Even if an early physical instantiation is completely wrong, they may be able, upon interacting with the object visually and tactilely, to agree that it is wrong, and thus move toward another instantiation that is more aligned with their shared design vision. Building consensus over relatively simple or obvious ideas may also help to foster team cohesion, which may later support resolution on more contentious disagreements. The motto of design consultancy Ideo, "Fail often to succeed sooner" (Fredman, 2002, p. 56), provides a short, yet profound guiding principle for the students regarding both design and argumentation.

5b. Classroom Norms of Accountable Talk

In addition to, or perhaps in lieu of, pragma-dialectics, the tenets of *Accountable Talk* (AT) (Michaels, O'Connor, & Resnick, 2007; Resnick et al., 1993) may be worth considering as a scaffold for argumentation in design. An overview of those tenets and how they align to PD theory is provided in Appendix I. Briefly, in classroom discussions, students should be held accountable to knowledge, to reason, and to community. PD theory describes such accountability as necessary obligations for discussants engaged in resolving differences of opinion. Although the PD obligations are more specific, they may be less attainable or understandable by students than the tenets of *Accountable Talk*. Therefore, those AT tenets may be emphasized, discussed, and woven into the classroom culture as an acceptable and motivating basis for all discussions, team design notwithstanding.

The importance of being accountable (and of being held accountable) when expressing opinions cannot be overemphasized. We are all too well aware of the devastation wrought by unsubstantiated opinions set loose within the public discourse. I am stating this here because a long-term objective of Resnick, Michaels, and O'Connor—the creators of *Accountable Talk*—is preparing students for participation in reasoned civic discussions (Michaels, O'Connor, and Resnick, 2007). Certainly, in a science or engineering classroom, AT can help promote scientific literacy, but science classrooms also provide a setting for learning how to be accountable in discussions with one's peers. The same could be said for novice engineering design—it provides a relatively low-stakes environment in which students can learn to be accountable for the opinions they express as well as to be accountable for listening to, and engaging with, the ideas of others so that resolutions can occur. Whereas argumentation may be a useful scaffold for learning design, design may become an environment in which to practice reasoned discussion among peers. Students can practice the techniques of resolving differences of opinion when the differences may not be as emotionally charged or culturally contentious as those found in civic life.

Suggestions for Future Research

Implementation of any one of the above recommendations (1-5a) is worth studying. Each recommendation could be the focus of a classroom observation study, or a combination, perhaps, could be a basis for an extended design based research program. I'm not going to lay out the particulars here. Suffice it to say that engineering design instruction at the high school level is new, so the avenues for potential research are wide open. The NRC (2009) called for exemplar studies of engineering education in K-12. This dissertation may be considered one such study, and my list of recommendations to educators could for a basis for several more.

Personally, I urge researchers to conduct studies of classroom environments that nurture intuitive thinking, design creativity, communication—especially in the form of argumentation—teamwork, reflective design practices, and analysis—again, in the form of deliberation and argumentation. I believe that showing students that they too can figure out complex design challenges while sharing their own ideas and building upon the ideas of others represent huge educational victories. For this dissertation, I chose not to directly ask students questions about their design thinking and communication. For future studies, I would strongly consider doing so.

OBJECT-BASED ARGUMENTATION

To my knowledge, object-based argumentation is not a term of art or a theory in its own right. Yet, I have been describing just that without using that term specifically. Further, I believe that such a theory is worth exploring. It may help to support instruction and learning in environments where artifacts and objects play important roles, e.g., engineering design. It may help to support the conveyance of tacit knowledge within organizations. It may also help to provide a bridge between intuitive and analytical problem-solving within teams.

I first began this research with the desire to explore the boundaries between school and work under the belief that people in each environment can learn from each other. Beliefs and practices of one can inform the other in a mutually beneficial exchange of knowledge and know-how. My intention is to explore that boundary further while developing and using a theory of object-based argumentation.

CLOSING REMARKS

To be honest, I never really saw Mr. Sperry's robotics course as a "classroom" per se. Sure, there were students, and teachers, and notebooks. The room was in a school, and there were bells, hallways, lockers, and lunch rotations. The students were looking forward to graduating one day. All the trappings of school were there. What I saw, at the end of the day, is that the students had a job to do, as did Mr. Sperry—the instructor, and Bill McKenna—the researcher. It was a learning environment for all of us—everyone in the room—and our job was to learn and teach. Here at the end, where lies the boundary between learner and teacher I cannot say. Likely, there is no boundary.

Appendix A: Timeline of the semester, Spring, 2010

Event	Duration	Result(s) of this stage	Data Gathered
Brainstorming at individual, group and class levels.		Potential design concepts and a list of functional requirements for each robot type.	Early concept drawings, functional requirements, classroom observation notes.
Team formation (within class sections). Teams were based upon student preference and specific personnel decisions by Mr. S.	2 class days	SolidWorks concept drawings and a design proposal. Every team (4-5 students) in every section created a design proposal.	Design proposals.
Team Pair formation: Teams across sections were matched by Mr. S. and myself based upon design proposals.	1 class day	Cross-section team pairs that would begin to discuss how best to combine elements from each team's proposal.	Team member assignments.
Cross-section team deliberation and robot assembly.	13 class days	Completed robot	Video (Rail1, Stat1); Google Documents; observation notes.
Mid-project student interviews	2 class days		17 interviews (video)
Mid-term class discussion—end of CAD phase	1 class day	Shared perspectives on project thus far	Whole class discussion (video)
Professional engineer interviews	1/2 class day	Students watched one video	None
Notable Sperry talk 1 G-Doc instructions		Demonstration of expectations and acceptable behavior	Indications of classroom culture
Notable Sperry talk 2		Demonstration of expectations and acceptable behavior	Indications of classroom culture
Final class presentations	1 class day		Team presentations (video) and slides
Final group interview	1 class day		Interviews of both sides of two team pairs: Rail1 and Stat1 (4 total).

Table A-1: Semester Timeline

Appendix B: 2010 Robotics Challenge

Setup
As part of a major installation of a city art project, you are asked to design two components of a robotic Goldberg machine. Your components will combine with others to form a large robotic art installation.

Robots
3) Pickup and Dropoff: This robot must move along a 3" diameter tubular rail that is approximately 7 feet long. This robot must also collect 4" diameter balls which rest on a shelf just below and to one side of the tubular rail. These balls will rest 6" apart as measured from the center of one ball to the center of the next (6" on center). Additionally, a third row of balls will sit in the middle of the shelf. These balls will be placed at varying heights. Each ball must be delivered to a launcher robot positioned on the ground about 5' below the tubular rail. The position of the launcher robot is fixed.
4) Catch and Fire: This robot rests on the ground and receives balls dropped from the Pickup and Dropoff robot. Catch and Fire must then shoot the balls through a specified target zone, black balls to the black target and green balls to the green target.

Game Specifics
- You will be able to control your robots manually at first, but by a specified date (TBA), each robot must operate autonomously.
- You may use additional materials to build your robot.
- Points:
  - (1 pt.) Ball picked from shelf and dropped
  - (2 pts.) Ball picked from shelf and dropped into Catch and Fire robot
  - (1 pt.) Ball launched through target
  - (2 pts.) Ball launched through target of correct color
- Pick-up and Drop-off
  - Pieces of tape along the tubular rail will coincide with the center of the balls on the shelf.
  - Balls must be dropped *without stopping the robot.*
  - Robot can be designed to fit completely around the 3" diameter tubular rail, if desired. Game apparatus will be disassembled to accommodate this.
- Catch and Fire
  - Robot rests on the ground, and its position is fixed.
  - Robot must fit within a box measuring X x Y x Z.

Teams
You will work in a team of 4-5 students designing one of the two types of robots. Your team will need to coordinate its efforts with other teams in your class as alliance

members during game play. Cooperative strategies, alignment of designs and communication between robots may all be things for your team to think about and discuss.

Team Roles

Each team will have four member roles with specific duties to perform. In the case of a 5 member team, duties will need to be shared. At different times throughout the project, each role will assume the role of team leader. For example, during the design phase, the CAD Manager will be in charge.

Team Member Role	Responsibilities
Build Manager	o Understand and describe the current build of the robot: ▪ how strategy and design fit together ▪ specific mechanical features ▪ principles of physics supporting the design[38] o Maintain a parts inventory o Maintain a photographic record of the build process o Help insure team productivity
Automation Manager	o Understand and describe the current program version: ▪ how the program fits with strategy and design ▪ specific programmatic features ▪ how the program works with the physics behind the design o Insure that robot brain is programmed correctly and that the robot is behaving predictably o Maintain program versions o Help insure team productivity
CAD Manager	o Understand and describe the current robot drawing: ▪ how robot is represented in CAD ▪ workings of sub-assemblies and how they fit together ▪ accuracy of representation ▪ Can someone not on your team build the robot from the drawings? ▪ Show how your robot relates to other robots and the game apparatus. o Maintain drawing versions. o Help insure team productivity.
Project Manager	o Understand and describe the overall picture of the project: ▪ How do the robot, program, drawing, strategy fit together? ▪ Report on coordination efforts between teams. ▪ Describe set-backs and accomplishments during the life of the project. o Maintain project folder and flash drive. o daily accounts of who did what and for how long o Find answers to questions through other teams, outside resources and Mr. Sperry. o Help insure team productivity.

Table B-1: Robotics Team Member Roles

About Member Responsibilities

Although different members are responsible for different things, these responsibilities are not exclusive. Each of you should understand something about the robot, strategy, drawings, program, coordination with other teams and the overall progress. It's *your team*, and you have to help make it successful. Some days the Project Manager may have do some programming, or the Build Manager may have to attend to the project folder. Help each other out as best you can.

Daily Routine

Each work day will be split between meeting time and work time.

1. Collect project binder and flash drive.
2. Review previous days' work.
3. Examine and discuss what you cooperating team has done or suggested.
4. Make a plan for today.
5. Work on that plan.
6. Review and make notes on today's efforts.
7. Store latest electronic file versions on flash drive.
8. Communicate with cooperating teams.
9. Return project binder and flash drive.

Assignments

Ongoing
- A. Project notebooks
- B. On-line discussions

Initial Design Phase
- A. Design proposal (in exchange for metal)
    - a. Items to include in the proposal
        - i. Description of strategy
        - ii. CAD drawings of the robot including isometric and other views
        - iii. Mathematics and physics based predictions of the robot's performance. Ex. a mathematical explanation of why you expect the launcher to hit the target. This shall include equations and graphs.
        - iv. Projection of the number of man-hours dedicated to each portion of the project: design, build, test, redesign, etc.

Testing and Design Iteration Phase
- A. Submit request for test document to another team for testing
    - i. Things to include
        1. Specific requests for the components you want to be tested
        2. Basic description of what the robot *should* do
        3. *Do not include* specific performance information
        4. Operational instructions
- B. Test report submitted back to design team
    - i. Things to include

1. Detailed description of the object under test. A third party should be able to determine which robot was tested based solely upon the description.
2. Detailed description of the test method, apparatus, and procedure.

Test results including synopsis, data tables and graphs.

Appendix C: Functional Requirements

FUNCTIONAL REQUIREMENTS FOR STATIONARY ROBOT

GENERAL	**ROBUST DESIGN**
must be able to fit in 18x18x18 box	design is simple
All cords must be out of the way	design is efficient
	design is durable
BALL COLLECTION	design must be original idea
Holds 5 preloaded balls	have an economical use of materials
must not let balls bounce out	economical use of materials
secure balls	fail safe
loading ball mechanism (funnel)	
not get clogged	**SENSORS/PROGRAMMING**
Catch balls successfully	must differentiate between green and black balls
Big enough basket to hold several dropped balls	Ability to change goals based on ball color
Maximum basket opening area is 1 sq.ft.	Ability to tell when a ball has entered the robot
Stable	Ability to turn motors on/off based on ball availability
SHOOTER	Throw ball when sensed
Accurately shoot balls into the goal	Ability to tell when to load a new ball
Ability to adjust power, speed, angle	Ability to tell when or when not to shoot
must have sufficient power to launch balls	communication to top robot
Efficient use of motors	Needs position information
	simple program

FUNCTIONAL REQUIREMENTS FOR RAIL ROBOT

GENERAL	**ROBUST DESIGN**
All cords must be out of the way	design is simple
	design is efficient
GRIPPER	design is durable
can reach balls of various heights	Good use of materials and power
can reach balls of various depths	design must be original idea
accurate, controlled grip	have an economical use of materials
gripper functions quickly	economical use of materials
gripper can function within a reasonable margin of error	fail safe
gripper has strength to grab firmly seated balls	
maintains firm grip of balls	**SENSORS/PROGRAMMING**
can collect multiple balls before drop off	distinguishes between different colored lines
Can quickly & accurately release ball	able to count lines
	Ability to tell when or when not grab a ball
MOTION	able to detect the presence of a ball
Accelerates quickly	Ability to tell when or when to drop a ball
travels smoothly	communication with bottom robot
wheels grips rail firmly without slipping	Needs position information
maintains balance & stability	simple program

Table C-1: Robot Functional Requirements

Appendix D: Design Proposal Guiding Questions

Robotics I, Spring, 2010: Design Proposal Questions

Directions: Use these questions to guide you through the design proposal. In the end, the proposal should look a short paper (about 2 pages) that describes your strategy and components of your design. Also include several screen shots from SolidWorks that represent your design well.

Stationary

1) How does the catch mechanism reduce the impact of falling balls?
2) How many balls can be in the robot at one time?
3) How/where does the robot sense ball color?
4) How does the robot know that it has a ball to shoot?
5) How does the robot know when to load a new ball into the shooting mechanism?
6) How are the balls moved into the launching system?
7) How are the balls launched?
8) How does the launcher adjust for various target locations?
9) How are motors used in this design? What are their functions? Do the motors turn off when not in use?
10) What are some design features that make the robot durable?
11) How are parts used efficiently? Do certain parts perform more than one function?
12) How does your design minimize the use of extra materials?
13) How does the robot communicate to the rail robot?
14) How might the robot communicate with different rail robots?

Rail

1) How does the robot accelerate and decelerate along the rail? Can it do so quickly?
2) How does the robot maintain balance on the rail?
3) How does the robot reach balls at various heights and distances?
4) How does the robot distinguish between different line colors?
5) How does the robot count lines?
6) How does the robot know that a ball is available?
7) How does the robot know that it is holding a ball?
8) How does the gripper collect and hold a ball?
9) Does the gripper function within a reasonable margin of error?
10) How are the balls released quickly and accurately?
11) How does the robot know when to release a ball?
12) How does the robot communicate with the stationary robot?
13) How might the robot communicate with difference stationary robots?

What design features make the robot durable?

Appendix E: Student Design Proposals

Rail 1, Period 3

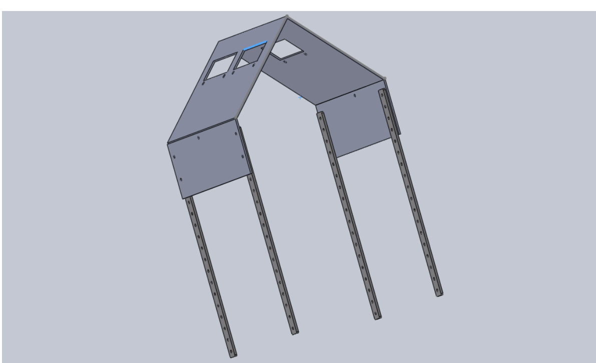
Okay. So let's have some sections:
Frame (house)

- roof
- wheel + motor
- posts

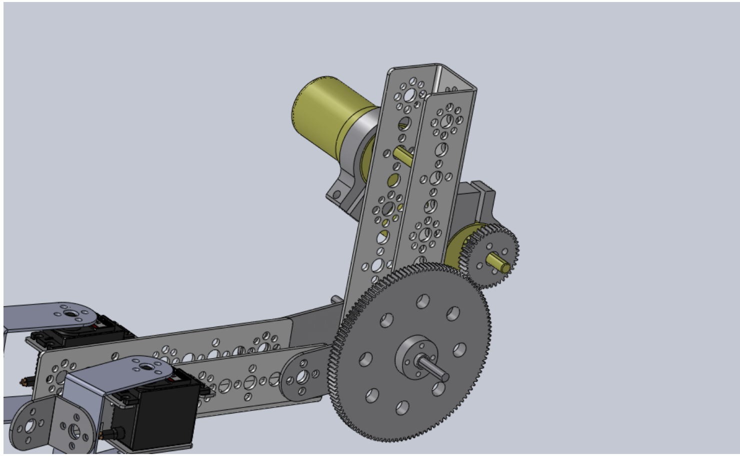
Arm
Claw
Funnel
Autonomous

And here we go!

Le Frame:
The frame of our rail robot looks like a house. It has a roof that is angled at 90°. It is angled as such so the wheels grip the rail diagonally, instead of straight up and down. This way the robot will be more balanced. The robot is also bottom-heavy, so it will be balanced further as such. The roof has 3 rectangular sections cut out of it for the wheels to go through when they are mounted. They will be mounted from the inside. If the wheels were mounted on the outside, the roof of the house would be dangerously close to the rail, and nobody wants that. Coming off the roof are two slats, going long-ways along the rail. These are completely vertical, not diagonal like the roof. Again, it's like a house! However, these slats do not go downwards very far. Coming off these slats are posts that are attached to the funnel. Oh yeah, by the way, the arm is attached to the slats. That's why the slats are there. So the arm can have a place to be mounted. Yeah. Anyways, that's the frame! Roof, slats, posts. Cool beans. Oh and this is made of plexan, or whatever that stuff is called.

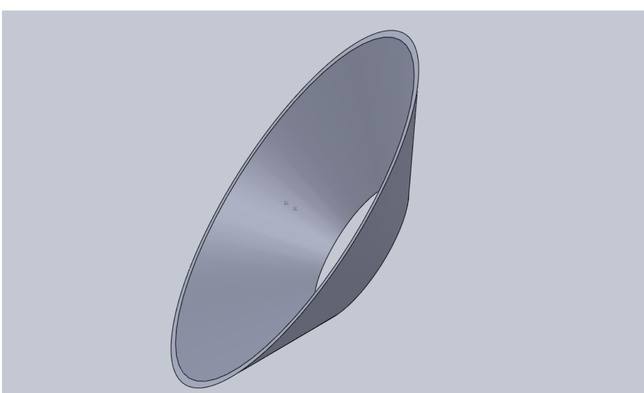


So balance: Yes, very much so.
Durability: Well, I don't really know what this plexan stuff is all about.



I hope it's durable.
Quickness: Yes, this robot has three wheels, therefore a high power level and much spee

Arm:
The arm goes as such: basically we have used a combination of two normal motors and two servo motors, to create an arm that moves with precision, and versatility. We are attaching our arm to the top of the frame, and from there it will be able to move up, down and will be able to grab the balls. We found that motors had too much power for our arm, so we geared the motor down to restrain the motors power and to allow the second part of our arm to move up and down. The arm can bend in two ways, like a rotating shoulder and an elbow. This way the arm can reach balls of different levels and it can also bend inside the frame to drop the balls into le funnel!!

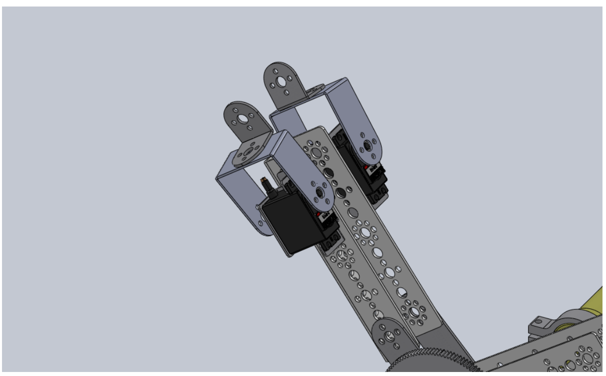


Funnel:

The funnel is a tool for the balls that we get off the board, and it sends them into the stationary robot, so that they do not go all over the place. It will be attached at the bottom of the robot. As the arm drops the balls into the funnel, the balls will line up all nice and be held there. Then some sort of mechanism will have to be put at the bottom of the funnel to keep the balls in until they are dropped, one after another, into the stationary robot.
This funnel contraption is a good idea because:

a. It gives a place for balls to be stored until droppage
b. It allows the balls to be dropped in a uniform matter
c. We can draw on the funnel and make it look pretty.

Note: The funnel will be curved away from the field for more room. It is also made out of plexan.



Claw:
The claw is pretty simple. It has one servo that turns one side of the claw. It grabs balls with the moving side of the claw and holds it up against the nonmoving side of the claw, like a pinch. Then it moves. This movement is somewhat precarious, but we imagine that it should work.

Autonomous:
We are very unsure in this aspect of the project. We are unsure of what sensors are available to us, and we also are very new at programming sensors and such. Some ideas are:

- Touch sensor on the claw to let the robot know it needs to grab the ball/ let it know it has a ball
- Light sensor to count lines to let the robot know where it is
- Touch sensor in the funnel to let the robot know that it is full

Bluetooth device to let the stationary robot know the rail robot is about to drop a load, if necessary

RAIL 1: PERIOD 5

Our robot is a rail robot and it is designed to pick up the balls from the platform and drop them into the stationary robot below.

The robot accelerates and decelerates along the rail by turning the motors on and off. This will cause the robot to stop and start wherever we want it to, which will allow us to pick up balls at every point along the rail. We believe that this method of using motors to move the robot will be effective and very efficient. Our robot only has two wheels so it would be quite imbalanced if we had not made several changes that will fix our problem. We added most of the weight to the bottom of the robot, so that gravity will allow the robot to stay on the top of the rail. We will also use the metal side supports to stay tight on the rail to prevent the robot from falling off.

Our gripper can move from side to side and up and down which will allow it to pick up balls at various heights and distances. Our robot can potentially pick up every single ball along the rail and pick up a lot of points. The gripper will collect and hold a ball because we will have several sensors located on the robot. The robot will have a touch sensor, an ultrasonic sensor, and a light sensor. All of these together will allow the robot to function very effectively and efficiently. The gripper functions within a reasonable margin of error not because of the wide gripper but because of the advanced sensors that we have on our robot. The sensors allow the robot to calculate exactly where the ball is and exactly where the robot needs to be to pick up the ball and drop it into the stationary robot. The grippers release the balls quickly and accurately so that it is capable up picking up balls and dropping them relatively quickly. The gripper can reach down, pick up the ball, move on top of the stationary robot, and drop it all in a very short time.

We intend to incorporate a light sensor into our rail robot, which will be able to distinguish between different line colors. This will allow it to stop directly under balls and pick them up with good accuracy and precision. We'll put a light sensor on the robot, which will allow it to count lines during the autonomous period. This will let the robot know when to stop and where to stop so that it can pick up balls. Without a light sensor we would missing the balls completely and be wasting precious time, costing us precious points. The robot will know if a ball is available by using an ultrasonic sensor that will know how far away the balls are. This will allow it to locate the balls, reach the balls, and drop the balls down to the stationary robot. The robot will know that it is holding a ball because we incorporated a touch sensor in it. The touch sensor will be located on the gripper and when the VEX ball touches the sensor, the robot will know that it has the ball and it is time to drop it into the stationary robot. The robot knows when to release a ball because of the touch sensor that is located on the gripper. When it grabs a ball it quickly moves on top of the robot and releases the ball. The robot communicates with the stationary robot, by the people in different groups talking to each other and deciding on important issues.

Our robot is quite durable because it has a very sturdy base that will definitely not break in this competition. Also many of the parts will not fall of because they will be attached with durable screws.

STAT 1, PERIOD 3

Them introductions:

Our robot is super special. It remains on the ground for most of its adult years. It has a stable base that is composed of two parts. The lower part is a simple four legged base. The upper section is a base with the same surface area as the lower section, it has wheels and a motor attached to the bottom of the top section of the base so that the upper section, shooter, and collection device can rotate like the turret of a tank. Its hopper consists of a funnel that feeds into a hollow tube. In turn the tube is directed towards the shooter. Our shooter is very similar to the boosters in those old hotwheel tracks. In the pipe two slits are cut away so wheels can be partially in the pipe, the wheels track being parallel to the side of the tubing. The wheels are then attached to two separate motors. Both of them will be controlled together but the overall speed of the ball can be adjusted easily.

Stationary Questions:

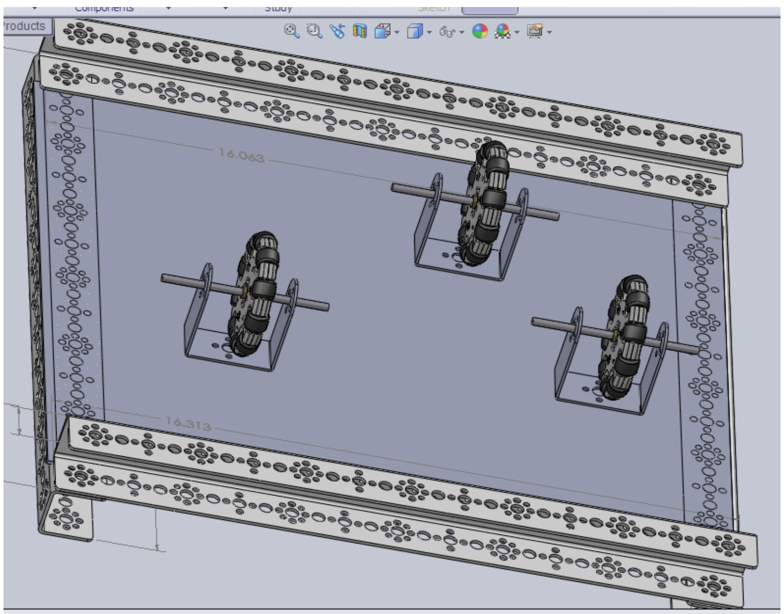
How the robot handles balls:

1) How does the catch mechanism reduce the impact of falling balls?
The funnel tapers down to the size of a ball slowing the balls down as they drop in.
2) How many balls can be in the robot at one time?
The robot can hold about 4 to 5 balls at one time.
3) How/where does the robot sense ball color?
The robot does not sense ball color.
4) How does the robot know that it has a ball to shoot?
The robot is manually powered so the person controlling the robot will see when it has balls and know to control the robot to shoot the balls.
5) How does the robot know when to load a new ball into the shooting mechanism?
It only holds balls when the trap door is closed which happens when the base rotates, at the start, and when it is told to by a controller.
6) How are the balls moved into the launching system?
The rail robot drops the ball into the funnel of the stationary robot and then the ball falls down the funnel to the shooter.
7) How are the balls launched?
There are two spinning wheels that the ball travels between to be launched.
8) How does the launcher adjust for various target locations?
The base rotates like a tank turret.

Engineering design of robot:

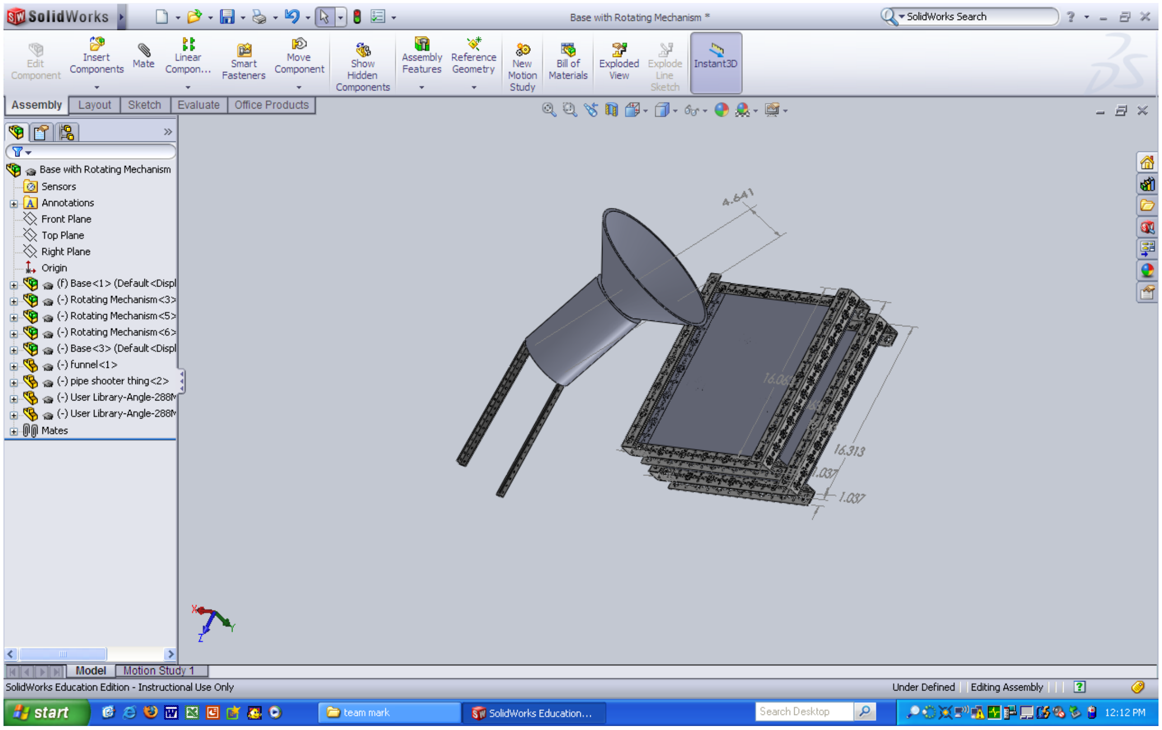
9) How are motors used in this design? What are their functions? Do the motors turn off when not in use?
Motors are used to spin the wheels for the launcher and to rotate the base. The motors turn off when not in use.
9) What are some design features that make the robot durable?
The base is very stable. And the top is weighted equally .
10) How are parts used efficiently? Do certain parts perform more than one function?
The funnel can hold balls and retrieve them from the rail robot. Other parts work on independent functions.
11) How does your design minimize the use of extra materials?
It is basic, and made mostly of larger parts.
12) How does the robot communicate to the rail robot?
It doesn't communicate. The robot is manually operated.
13) How might the robot communicate with different rail robots?
Same as above

Pictures of Our Virtual Construction Process:



The Rotating MechanismInstallation

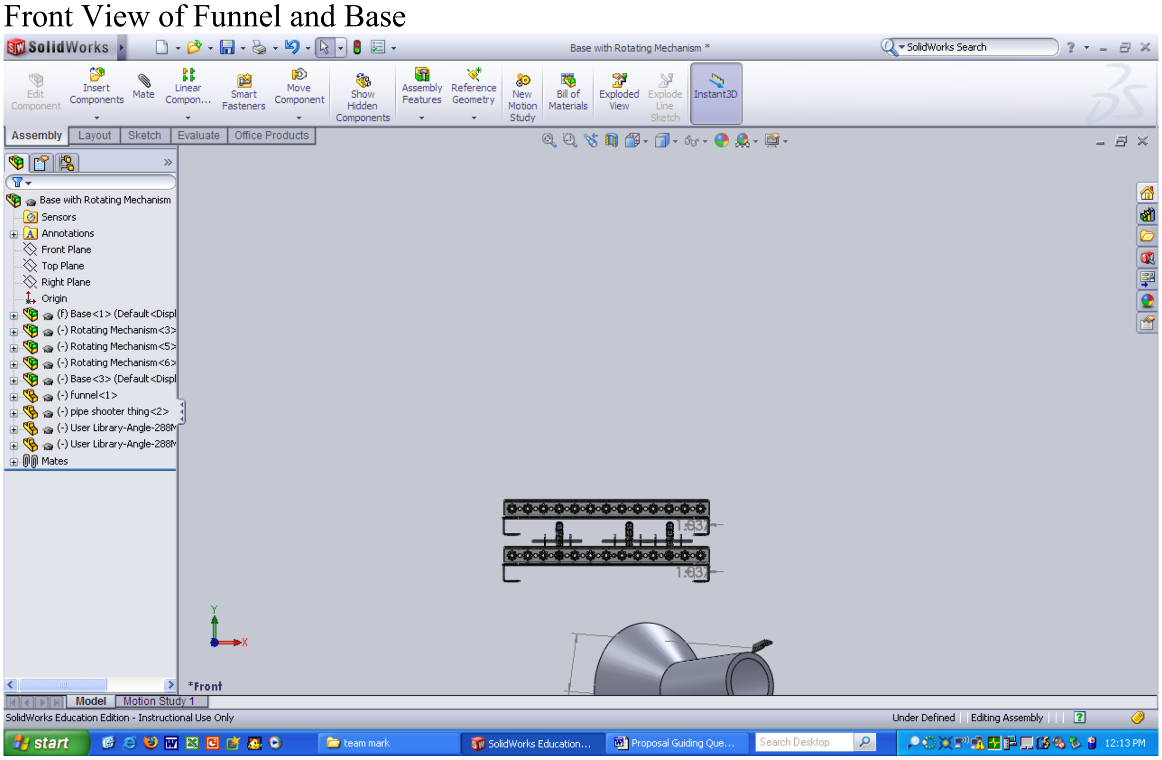
This is the base and the funnel and shooter are mounted on top of this. A motor goes through the middle and spins the body of the robot which is free to turn because of the wheels on this base.



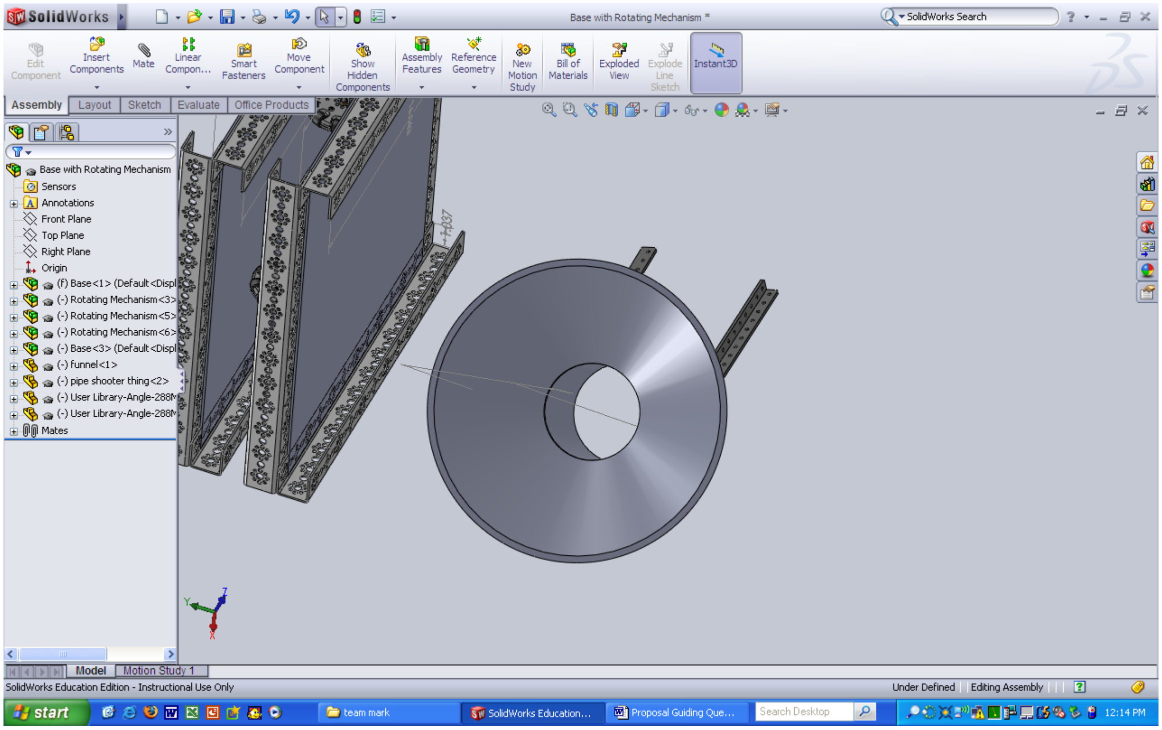
Funnel alongside with the Base

This funnel is designed to specifically lead the balls to the shooter which will project the balls towards the goals.

Front View of Funnel and Base



As described, the funnel is designed specifically to lead the balls one at a time to the corresponding shooter side of the goal.



The Funnel as shown in close up, with a slight bump right before the entry to hold up balls and prevent ugly stacking.

STAT 1, PERIOD 5

Our stationary robot will be comprised of basic systems: funnel, sorter, and launchers; each of which contains complex sub-systems working together. The beginning of our robot is the funnel, which will be comprised of a foam funnel braced with flat brackets in order to help overall durability of the funnel. Our next component is the sorter, which will contain slowly counter-rotating wheels in order to give the sorter doors time to read the ball's color and open the appropriate door. The sorter itself is comprised of tubes held together by L-brackets, with rubber bands strung around the tubes to keep the balls inside the sorter. The final component of the robot's main design is the launcher, comprised of a motor at the end of the launcher, with gears decreasing in size to the back of the launcher as to gear up the wheels for more power. (Note: Gear ratios can be changed in order to change level of power in launcher wheels.) The launcher base will be made of a plastic bottom, since there is no metal between the launcher sides themselves.

1) How does the catch mechanism reduce the impact of falling balls?

Rubber bands in the ball reservoir will reduce the impact.

2) How many balls can be in the robot at one time?

That hasn't been determined yet, but it's pretty easy to modify to hold more, so that won't be a problem.

3) How/where does the robot sense ball color?

It senses the color as it slowly takes the balls in from the funnel and from there it sorts it into it's appropriate launcher.

4) How does the robot know that it has a ball to shoot?

We planned on having a motion sensor by the launchers so the robot knows when to fire.

5) How does the robot know when to load a new ball into the shooting mechanism?

The balls are going to be fired immediately once they've been sorted so there is no need for the robot to know

6) How are the balls moved into the launching system?

After getting sorted by the light sensor, they fall into the launcher by force of gravity, and get fired into the appropriate goal.

7) How are the balls launched?

There will be two wheels next to each other spinning in opposite directions fast enough so that once the ball enters it will get fired.

8) How does the launcher adjust for various target locations?

We will have it set up so the trajectory of the balls will be at the right angle for either side. If that doesn't work, we'll make the ramp have a pivot so it will you can adjust the angle it's firing at.

9) How are motors used in this design? What are their functions? Do the motors turn off when not in use?

The motors are left on for a majority of the time. Their functions are: shooting/sorting the balls. We could set up the launcher motors so that they turn off when the motion sensor isn't activated. Though, this might cause a problem because if it launches a ball while it's getting up to speed it won't shoot it with its full potential.

10) What are some design features that make the robot durable?

Beams in a way that will make it more durable will support everything

11) How are parts used efficiently? Do certain parts perform more than one function?

No all the parts perform one function, though they all run in an extremely efficient fashion.

12) How does your design minimize the use of extra materials?

It uses rubber bands where metal could be used in its place.

13) How does the robot communicate to the rail robot?

It doesn't communicate with the rail robot there is no need.

14) How might the robot communicate with different rail robots?

It won't communicate with the rail robot.

Design Proposal

The robot we designed is able to accelerate and decelerate using a complex motor mechanism to power 3 wheels. There will be one wheel placed on top of the rail and the other two will be placed on either side of the rail allowing the robot to perform a sort of tilting maneuver to adjust for different locations of the balls. Also by having wheels on top and on bottom, it allows for our robot to have more stability when moving. So no matter if the robot tilts to a side or completely rotates around we will still be able to have forward and backwards movement.

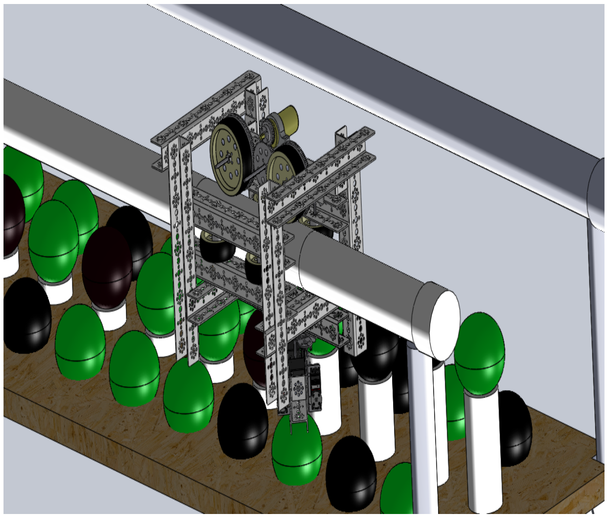
We as a group also thought that the robot should include a light sensor. The light sensor allows the robot the ability to detect certain colors. Which gives the robot the ability to go for the more valuable balls first and allow our group to score more points than the opposing team. In addition to the light sensor, the robot will also have a sonar sensor in order to detect and perceive the distances and varying heights of the balls. The gripper will use a rail with powered wheels attached to pick up balls. It will do this by running over balls, spinning the wheels that will pull the ball into a tube-like structure with additional powered wheels on each

side of it pulling balls up into it. In a way this gripper has a vacuum like effect. We have designed our robot in a way in which that the chamber that holds the balls will be able to hold at least 3 if not more at a time.

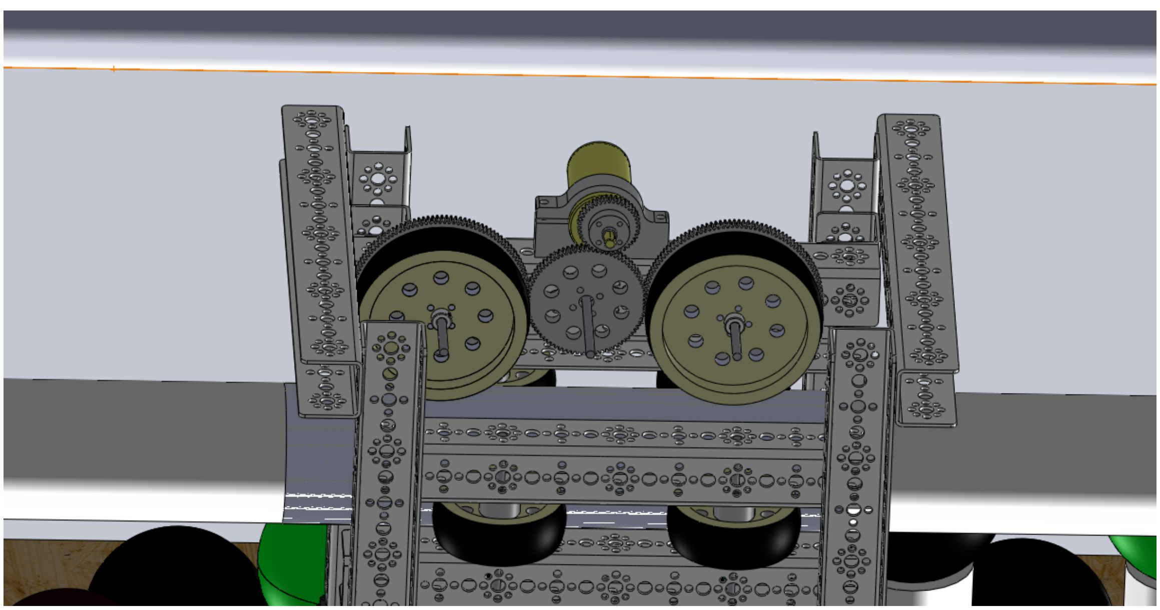
The tilting function of the robot will allow us to drop the balls straight out of the tube into the other robot. We are planning on communicating with the robot on the bottom through Bluetooth. So our partnering robot will have to either already have Bluetooth or be able to be equipped with it quickly. Through communicating through Bluetooth, it will allow us to know the exact location that the robot needs to drop balls. To release these balls we will slowly reverse the direction in which the wheels are spinning. This will allow the balls to drop out of the tube and down to the stationary robot. Although our robot may not be the most durable it will be effective while it isn't experiencing technical difficulties. Also because of the simplicity of our design, it might appear to be difficult but in all actuality we only have three parts to our robot.

8th period

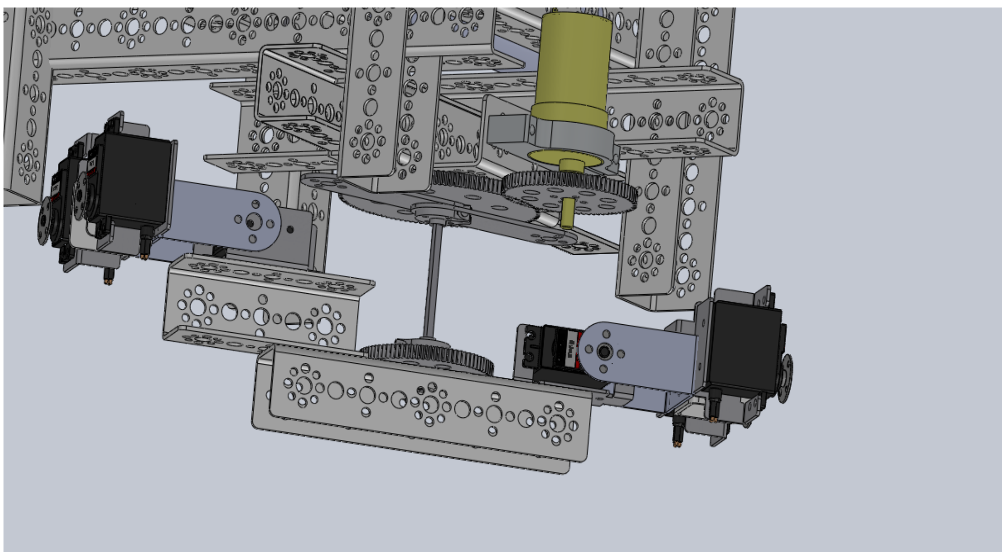
Robotics Design Proposal



Our robot is driven by one motor driving 2 wheels using gears. The gear ratio is 1:3, but we are using the 101mm wheel, the robot should therefore go at an average speed. We have four small wheels on the side of the rail, two on each side, that press against it and that allow us to have perfect balance.



There are 2 grippers on one arm that can rotate at more than 360 degrees. One side is shorter and lower, and grip the first row of balls. The second one is ½ an inch higher, about 2in longer and can grip the balls on the 2, 4, and maybe 6 in standoff in the middle. At the end of the servos, we will have plastic claws to grip the ball. Each claw uses 3 servos, making it very precise and able to move on 2 axles (up-down, close-open). 2 servos will close a semi-sphered shaped claw and the third one will lift the ball off the plate. Once the ball is over the other robot, the robot will drop the ball by releasing the claws. We will make the claws bigger than the ball to have some margin for error. Both of the servos controlling the claw can be moved together and fast, therefore the release



will be quick and accurate.

A pedometer on the wheel will tell the robot its absolute location. We will have a light sensor on the front and back of the robot . The robot will also be coded so it will count the number of lines it crosses and can calculate its location on the rail, in addition to the pedometer,and each sensor will correct each other. A second pedometer on the motor turning the claw will tell the robot which claw is in release position. An ultrasonic sensor inside the claws will tell the robot if a ball is available before it tries to grab it. A touch sensor next to the ultrasonic sensor will confirm to the robot that it is holding a ball and let it know when it is released. Our robot is self sufficient to know when and where to drop a ball and does not need to communicate with the other robot in order to pass on the ball. The whole frame is built out of c-channel, making it very sturdy and durable. Mechanically, nothing is fragile, since everything has a lot of contact points. Electronically, all our sensors are backed up with a second type of sensor for accuracy.

Appendix F: Excel Coding Tables

Table E-1: Stat 1 Analysis Table (Sample)

Base	Funnel	Shooter		D	U	Stat 1	Task	PR	Questions	Answers	Dynamics	Agreement	Inviting Ideas	Inviting Questions	Praise	Drawings	Object	Sperry	Elements
Base			3rd	1	1	i think that our group should start building the base because our base design enables the robot to rotate and aim left and right.													Elements
Base			3rd	1	2	and if we build the base first we will be able to adjust all of the other components to a size that will work well.													Elements
Base	Funnel	Shooter	3rd	1	3	Besides those suggestions, everything is fine! Incredible design.			Questions						Praise				
		Shooter	3rd	1	4	The shooter looks very efficient and incredible.				Answers					Praise				
		Shooter	3rd	1	5	The question is, how are the balls going to shoot from the shooter when there is no sort of blockade right before the shooter to hold the balls in place till they get shot from the robot?			Questions										Elements
		Shooter	3rd	1	6	Also, the shooter looks perfect but couldn't you make it a little shorter? It will help the robot rotate faster and			Questions										Elements
	Funnel		3rd	1	7	I am concerned that the it will be really complicated to operate a ball sorting device with the sensors and might require to many materials but if y'all can make it work then go for it.													Elements
	Funnel		3rd	1	8	We are planning to wait on making the funnel until sperry gets us the sheet metal so we can form it to what we want it to look like.													
Base			5th	1	9	Anyways, i hope that i have cleared up the problems, and i would agree with building the base first in order to have something to build on for both groups.						Agreement							
Base			5th	1	10	However, i feel that with a rotating base the robot can easily become misaligned.													Elements
		Shooter	5th	1	11	About the rotation problems, in our design we had no plans to have the shooter rotate; in fact, our plans were to have two identical launchers aimed at either goals in order to avoid having to rotate and possibly become misaligned.													Elements
Base	Funnel	Shooter	5th	1	12	I think that we should start by comparing designs. So that way we can see how each other thinks to start on the road of compatibility. If you submit your design proposal we can start tobuild.					Dynamics								
Base			5th	1	13	How will the base of the robot rotate? Currently I just see that there are 3 wheels all facing in the same direction with no motors powering it and don't understand how it is supposed to function. I suggest that if you still want it to rotate that it should have 4 wheels instead of three so that the rotation would be simpler.			Questions							Drawings			Elements
Base	Funnel	Shooter	5th	1	14	First I think that both groups need to agree on one design before we can start building the robot. Possibly list out the pros and cons of each design, distinguishing which robot is more reliable/stable.					Dynamics								

Table E-2: Rail 1 Analysis Table (Sample)

Arm	Claw	Drive	Funnel	House	P	DAY	U	Text	Tasks	PR	Questions	Answers	Dynamics	Agreement	Inviting Ideas	Inviting Questions	Praise	Drawings	Object	Sperry	Elements
Arm					5th	**1**	1	I like the idea but i'm not sure how the arm will get the balls to the funnel and we also need to figure out where to mount the funnel so that it's not in the way.			Questions			Agreement			Praise				Elements
	Claw				5th	**1**	2	I would also add some sort of rubberband type of material so that it's easier to grip the balls.													Elements
			Funnel		5th	**1**	3	The only concerns that i have is the funnel. I like the idea but i'm not sure how the arm will get the balls to the funnel and we also need to figure out where to mount the funnel so that it's not in the way.			Questions			Agreement							
Arm	Claw	Drive	Funnel	House	5th	**1**	4	Other than that y'alls robot design is awesome!									Praise				
Arm			Funnel		3rd	**2**	5	I think the changes that you suggested are good and the funnel will be mounted near the bottom and it will be slightly bent so it will be easier for the arm to move back and drop the balls.				Answers		Agreement							Elements
				House	3rd	**2**	6	it's easiest to think of the arm as a real arm and shoulder that folds up and bends back sort of up into the house and drops the ball downward.													Elements
Arm			Funnel		3rd	**2**	7	Yeah the funnel and arm will need some tinkering but in general the funnel is going to lean away from the ball mount so it doesn't run into anything.				Answers									Elements
Arm					3rd	**2**	8	The arm is complicated too... it's easiest to think of the arm as a real arm and shoulder that folds up and bends back sort of up into the house and drops the ball downward.				Answers									Elements
			Funnel		3rd	**2**	9	maybe we'll make a video :) Does anybody have any ideas of how we can shut off the bottom of the funnel to hold in the balls until dropoff?							Inviting Ideas						
		drive			5th	**2**	10	I'd say that on Thursday yall can start working on the drive train and we'll continue in 5th period.	Tasks												
			Funnel		5th	**2**	11	Ok, trial and error works for me w/the funnel.					Dynamics								
			Funnel		5th	**2**	12	The hold the funnel closed we could use like the same material to create a cap and use like a servo to open and close. Or we could figure out how to put the cap/lid on like a linear slide so the cap slides horizontally and lets the balls out. Any suggestions?				Answers			Inviting Ideas						Elements
				House	5th	**2**	13	We could have the rubber tipped gripper have the same idea as the base, like so it's a hinged flap at the bottom with the same rubber material maybe?													Elements
Arm	Claw	Drive	Funnel	House	5th	**2**	14	Can we really do trial and error? If one group figures a way to make it work, can the other group default accept it, or should we both try to create one and see which is best?					Dynamics								

Appendix G: Discourse Code Samples

Design Elements (Elements)

Any reference to specific design elements or the design as a whole. Design Elements can exist as ideas or as attributes of a physical object.

- I dont think the claw has to be curved because that would just make for more work, I think as long as the things used to grip the balls aren't round we should be fine with the design.
- If we can figure out our final design then we can ask [Mr. S.] for the parts!
- I personally think that we should make the arm itself shorter so we can make the claw longer.
- the basket might be a good alternative for the funnel but how exactly is that going to work?

Drawings

Any reference to the drawings or design proposal.

- I wish we could show yall our solidworks because that would make explainations and descriptions of potential changes much easier.
- Also, did you find the complete assembly of the robot? We tried to find some solidworks on mine also but the solidworks won't work whenever our group tried to open it.
- It is important we don't just follow the solidworks blindly, because this might lead us to wrong design, so just look at the solidworks for concept and build it from there.

Object

A reference to a physical object that is used as an explanatory device. It can be any physical object (not just their robot) as long as it is used for this purpose.

- I could not relate the base that you built to the drawings of your bot so i was unable to complete the frame as planned.
- because it's really simpl to all e, we got the claw idea from the very first like demo rail robot that sperry showed us. If you guys remember what that looked like you can just set it up like that.

Assigning Tasks (Tasks)

Declarative statements regarding what an individual or team will do. Also, imperative statements directed at someone other than the author, usually the other team. These imperative statements can be written in the form of a question, "Will you do the following?" The quantity of Tasks by a particular team may also indicate whose ideas are being adopted. They can also be indirect speech acts promoting support for a particular design.

- For Thursday could you guys start on the frame design

- Mr. S. and I came to an agreement that we are going to add PVC pieces onto the claw for it to have maxinum contact with the balls.
- Go ahead and leave the ball/ball sucker alone and work on attaching the drive train to our frame. We are going to need the support that ours provides

Note that the second statement is also coded as PR and Mr. S., due to the report on the conversation. It is also coded Design Elements because it describes specific desgin concept.

Progress Report (PR)

Statements about what an individual or a team or what they did.

- we worked on the lexan ramp. we bent it and might have it screwed in by the end of the period
- Sooooo I finally finished the arm!! but! to me it looks a little bit too long tell me what you think!

Mr. S.

Mr. S's name is mentioned. He is often used as an information liaison between teams.

- so i was showing Mr. S. our robot and he brought up a good point. what is the robot going to grip to grab the balls. those little arms wont grab it completely...we need to add some type of gripper to get a secure hold on it.

Agreement

An instance when a team member explicitly agrees with another or more than one other team member.

- We agree with your way of picking up balls. It is much more efficient than the claw that we thought of using. I'm just confused about how the wheels will reach balls of various heights.
- i guess ill stop worrying about the base turning, it will probably be close enough.
- I had the understanding that we were having 2 wheels so that is the reason for the 2 drive trains.

Questions

Honest requests for information or explanation. These need not be phrased in the form of a question, e.g. "I'm confused about…"

- We just put up the metal walls, but we didnt understand what you all ment by put it either parrallel to the pipe or running along it

Answers

Responses to previous questions. Unsolicited information or explanations are not coded as answers.

- alright, as far as the slanted portion of the robot, that is to aid the ball delivery to the shooter and will not throw off balance.

- the idea about the third wheel purely for weight can be more efficiently accomplished without a wheel. it seems to us that your idea will be far to cumbersome for it to work

Inviting Ideas

A statement that solicits ideas from an individual or the team members at large.

- Does anybody have any ideas of how we can shut off the bottom of the funnel to hold in the balls until dropoff?

Inviting Questions

A statement that invites questions for further information or explanation.

Praise

Favorable descriptions of the robot, statements of a job well done, general well-wishing.

- the drive train looks good!
- ok thanks yall for working on the arm.

Team Dynamics

Statements coded as Team Dynamics are statements that address issues regarding how the team is working through the process. These can include strategy suggestions, labor distribution, team communication, etc. Team Dynamics can also include statements about the respective position of the two pair teams.

- We don't want to shut you guys out, but we do want you guys to express your ideas more.
- Please give us something to work with though you kno? like you need to gives us more ideas if you disagree with ours.
- …if you want this to work we need to be one group and we need to communicate like that rather then yall talking to us like when you say funnel we should automatically be able to figure the dimensions and specs. you want help you need to learn how to ask and communicate to us any pertinent information. if you leave us to assume things we will, and when its not what you want and you change it you have no right to peg the blame on us. sorry if we havent done work but i dont see the reason to do work that will just be undone later.
- I feel that my group is better at being instructed that kind of just being creative... so i guess it would help us if y'all would tell us what you want us to do (like m_'s comment above). But if thats too much to ask for then we will work harder on that.

Appendix H: Team Final Presentation Rubric

The following was handed to the students prior to making their final presentation.

Presentation Outline

*Every team member should speak the same amount of time.
**This is a celebration of all your hard work! Go ahead and show off a little!

1) Title Slide (1 slide)
   a) Team names
   b) Robot type and number
2) (2-3 slides)
   a) What functional requirements influenced your design the most?
   b) What subassemblies were the most challenging?
   c) Why is your robot cool? Describe specific functional, design, or aesthetic elements.
3) Focus on the robot (2-3 slides)
   a) Describe particular mechanical challenges you faced.
   b) Describe how you altered your design to meet those challenges.
   c) Include photos of your robot to help describe a) & b).
4) Time Capsule
   a) If your robot were to be handed to another design team for future work, what messages, visions, ideas would you like to give to them?

Appendix I: Final Project Survey

Name:

Class Period:

Robot Team (Rail1, Stat4, etc.):

The results of this survey are confidential. Thank you very much for all of your hard work this semester and allowing me to hang out in your class!

1) The challenge was
   Too Easy — Too Difficult
   1 2 3 4 5 6

2) The communication within your class group was
   Inefficient — Efficient
   1 2 3 4 5 6

3) The communication with the other class group was
   Inefficient — Efficient
   1 2 3 4 5 6

4) How comfortable were you with the design challenge?
   Not comfortable — Very Comfortable
   1 2 3 4 5 6

5) I think that group work in general helps me learn.
   Not at all — A lot
   1 2 3 4 5 6

6) I think that I learned well in <u>this</u> group project.
   Not at all — A lot
   1 2 3 4 5 6

7) How useful was your CAD design?
   Not at all — Very Useful
   1 2 3 4 5 6

Comments (optional): Use back of page if necessary.

Appendix J: Pragma-dialectic Theory and Accountable Talk

Pragma-dialectic theory offers a rubric for speech acts which determines when and how the different types can (and cannot) be used during a critical discussion. These rules are primarily established in order to support transcript analysis. Leveraging these rules as guidelines for discussants, I believe, would be overly complicated and perhaps unnatural. Doing so would require the discussants to classify their own statements as types of speech acts in order to determine whether or not they are admissible at a given stage in the discussion. Developing such an awareness would certainly take practice, and it may also prove to be counter-productive.

By basing the theory on speech acts, pragma-dialecticians mean for PD to be a formalized extension of everyday conversations. It provides allowances for the dynamics of conversation but applies certain rights and obligations that guide discussants' participation. PD establishes nine rules for engagement in a critical discussion (van Eemeren & Grootendorst, 1992, p. 208-209). These rules are not easy, per se, but they don't require speech act theory to be understood by discussants.

1. *Freedom rule*

   Parties must not prevent each other from advancing standpoints or from casting doubt on standpoints.

2. *Burden of proof rule*

   A party that advances a standpoint is obliged to defend it if asked by the other party to do so.

3. *Standpoint rule*

   A party's attack on a standpoint must relate to the standpoint that has indeed been advanced by the other party.

4. *Relevance rule*

   A party may defend a standpoint only by advancing argumentation relating to that standpoint.

5. *Unexpressed premise rule*

   A party may not deny premise that he or she has left implicit or falsely present something as a premise that has been left unexpressed by the other party.

6. *Starting point rule*
   A party may not falsely present a premise as an accepted starting point nor deny a premise representing an accepted starting point.
7. *Argument scheme rule*
   A party may not regard a standpoint as conclusively defended if the defense does not take place by means of an appropriate argumentation scheme that is correctly applied.
8. *Validity rule*
   A party may only use arguments in its argumentation that are logically valid or capable of being made logically valid by making explicit one or more unexpressed premises.
9. *Closure rule*
   A failed defense of a standpoint must result in the party that put forward the standpoint retracting it and a conclusive defense of the standpoint must result in the other party retracting its doubt about the standpoint.
10. *Usage rule*
    A party must not use formulations that are insufficiently clear or confusingly ambiguous and a party must interpret the other party's formulations as carefully and accurately as possible.

Taken together these rules may be too complex for a classroom of novice students learning how to argue. However, these rules can more simply be understood as extensions of the tenets of Accountable Talk (Michaels & Resnick, 1993) which are currently endorsed in many K-12 classrooms today.

Accountable Talk (AT) prescribes that students remain accountable to their community of learners, to standards of reasoning, and to knowledge. All three must work in concert in order to promote learning with understanding for individual students as well as the community as a whole. Briefly, accountability to community happens when students attend seriously to and anchor their own ideas within the ideas of others. Accountability to standards of reasoning emphasizes using logic to form reasonable conclusions. By establishing a safe communal space of trust and an adherence to reason, students can move beyond attacking conclusions with personal intent to challenging the premises used to form conclusions. Challenging premises helps the community members to understand their own logical processes and avoids overly emotional attacks that can cause students to recede and damage the shared trust essential for meaningful discourse. Accountability to knowledge—knowledge that is accessible to all students--encourages students to get their facts right and to support their assertions with material relevant to the discussion at hand.

The tenets of AT are interwoven and emerge in conversation. Whether a person honors or denies them depends upon the kinds of statements or discursive moves he or she makes. The rules of PD address the discursive moves directly by considering them to be speech acts and by accounting for their explicit and implicit meanings. PD honors the tenets of accountability (community, reason, knowledge) together by commanding that discussants: (1) are able to express standpoints and doubts freely (Rule 1); (2) are obliged to defend a standpoint when requested (Rule 2); (3) stick to the standpoint at hand (Rule 3 & 4); (4) are accountable for all premises, both explicit and implicit (Rule 5); (5) adhere to community standards of reasoning (Rule 7); (6) honor previous agreements and rules of discussion (Rules 7 & 8), including when to begin and end (Rules 6 & 9). Whereas the tenets of AT are somewhat vague but easy to understand, the rules of PD are specific but difficult to routinize. Still, an advantage to PD as a pedagogical tool may be that desirable norms of classroom interactions and the rules of argumentation aren't separate. They are codified together into one single theory.

In regards to standards of reasoning, PD theory commonly refers to reasonableness criteria which place standards on the admissibility and validity of argumentation during a critical discussion. Reasonableness criteria are largely determined by the discussants but must also serve the resolution process. If the reasonableness criteria do not help move the discussion towards resolution, they are not admissible as critical assessment of the standpoint or argumentation at hand, even if the discussants agree upon them (Van Eemeren, 2006). Such criteria are often esoteric, depending on the subject matter and context. However, they can more simply be viewed as extensions of typical commitments made in everyday conversations. If the members of a discussion are engaged in a task that requires some solidarity, or they simply wish not to be at odds with one another, the Grice's cooperative principle applies (Van Eemeren, 1982; Grice, 1975). The principle describes common commitments of people attempting to make their contributions relevant to the conversation. These commitments apply to critical discussions, and it is usually the case that reasonableness criteria are presumed and not stated explicitly. In a technical context like design, however, reasonableness criteria may need to be made explicit.

In any attempt to resolve differences of opinion, especially in technical areas like design, clarity is critical. The discussants have to understand the standpoints, the challenges against them, and the argumentation clearly. This is the heart of Rule 10 of PD. Achieving clarity does not necessarily require overt explication, but this is often the case. Clarity could also be attained through the use of non-verbal communication like images, drawings, or objects (Van Eemeren, 2006; Van Reese, 2006). Artifacts supply information and meaning that defy verbal description (Polanyi, 1967; Schon, 1983; Starr, 1989), or they fill gaps in the discussants'' vocabulary. The PD rules for participating in a critical discussion are there to support clarity and mutual understanding among the discussants. They serve as guides to keep the discussion clear and progressing towards resolution. If standpoints, challenges, or argumentations remain unclear, it is likely due to the violation of one or more of these rules.

Appendix K: Brief Narrative of the Semester

Prior to the Spring, 2010 semester, Mr. Sperry and I concocted a design challenge for the spring term—the second semester for the Robotics I students who enrolled in Fall, 2009. We wanted a challenge that would be more difficult than those typically associated with TETRIX robotics competitions in order to stretch the students and see what they could accomplish. Given our requirement that the students would have to collaborate online with students from another class section, we knew that the challenge would have to be hard enough to warrant such collaboration. Mr. Sperry, with his 10 years of teaching experience, assured me that his students could smell a contrived classroom assignment a mile away, but they appreciated assignments that they perceived to have merit in terms of technical skills, professional training, and their own edification. In short our challenge had to be difficult enough to warrant the efforts of eight member teams and compelling enough to be worth the trouble of collaborating online—a mode of communication more cumbersome than face-to-face. Our design challenge succeeded in the sense that the students recognized a need for help from a group of students in another class period; moreover, the students collaborated with team members from the other class period quite well, despite experiencing some understandable frustrations.

Nonetheless, problems emerged that we did not anticipate. First, once the groups in each class period were formed, we asked each group member to assume a particular role: Build Manager, Automation Manager, CAD Manager, and Project Manager (See Appendix B for descriptions). Each team would thus have two students in each role—e.g., two Project Managers, one for each class period. The students assumed their respective roles, but the delegation of work Mr. Sperry and I had hoped for dissolved into more general "all hands" collaboration. I suspect that this happened because categorical delegation of work must be preceded by categorical distribution of knowledge. The students' design knowledge was certainly distributed, but piecemeal—they all had to pitch in to manage the project, create the drawings, build the robot, and so on. During my observations and subsequent analysis, I noticed that the effect of student roles on team collaboration seemed negligible.

By far the biggest setback was the use of the CAD system. Mr. Sperry chose Solidworks 2010[39] because of its use in industry and because TETRIX had created a library of parts that could be used in conjunction with Solidworks. This way the students would be able to create representations of their design by "assembling" parts from the library in Solidworks. Unfortunately, creating the CAD drawings took much longer than Mr. Sperry and I anticipated. The students experienced technical problems with the software or computers almost daily. Mr. Sperry, his student aide, and I provided tech support all the time. When the team's drawings were nearly complete, the school had a server problem, and nearly every team lost its work. This was a huge letdown for the students, but Mr. Sperry and I tried to recast it as a positive lesson in the value of keeping multiple backup files. (The school district had backups, but retrieving them took weeks—too long to support the students' build process.) After the server crash, the students were forced to recreate their drawings in just a few class days. Naturally, the last-minute rush job reduced the overall quality of the drawings. To be honest, the drawings the students lost weren't that much better than the ones the teams ended up using. In hindsight, the roughness of their CAD drawings shouldn't have been surprising, nor was it their fault. Learning CAD software takes time, and learning the software in the process of creating their robot designs (in the face of many technical difficulties) was too much to ask. That the teams had reasonable representation of their designs was a testament to their resolve and their ability to regroup after a significant setback. In short, when planning to use CAD systems for engineering design class, plan ahead, and add extra time.

Without good drawings, most teams had to design and assemble on the fly while communicating with their team members in the other class period. Although this process may have been educationally valuable, it was not efficient. Hence, the robot build time took longer than Mr. Sperry and I had anticipated. Most teams managed to assemble a working robot before the semester ended, but no team was able to program their robot so that its servos and motors could function. Without the control programs, the students were unable to see their robots operate or engage in any performance testing, an important section of the design challenge we created. This posed a limitation of the study

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[39] For technical notes on this release of Solidworks, see http://files.solidworks.com/Supportfiles/Release_Notes/2010/English/relnotes.htm.

because I wanted to compare the students' argumentation as it emerged during the design phase with what emerged during the testing phase, when they had a more or less working system. Based on my own professional experience in engineering and my understanding of classroom argumentation, I predicted that I would find notable differences in the discourse related to designing and to that of testing.

Despite the challenges and subsequent frustrations, all of Mr. Sperry's students faced the design challenge with resolve, creativity, commitment, and collegiality. My hat is off to them! The students' perseverance may be attributable to many things, including personal intrinsic motivation, participation in a collegial environment, Mr. Sperry's tutelage, or the school's robotics culture. My study didn't focus on these attributes, but I want to recognize them. This study may not have been a success without the important influences of Mr. Sperry, his classroom culture, and the school's culture.

Appendix L: Intentional Exclusions from the Literature

Exclusion of Shared Cognition Research

When studying teamwork, especially asynchronous teamwork, the literature on *shared cognition* (also known as team cognition, team mental models) should be considered (e.g., Cannon-Bowers, 2001; Stout et al., 1999; Hutchins, 1995; Mohammed, Ferzandi, & Hamilton, 2010 (a review); Salas & Fiore, 2004; Stahl, 2006). After reviewing this literature, however, I elected not to use it as a basis for my work. My reasoning for excluding literature on shared cognition was primarily motivated by crucial differences in the methodology, research settings, and sorts of outcomes deemed desirable in research on shared cognition.

That is, as Mohammed (2010) describes, “The basic assumption underlying this research is that teams whose members share models of both task work and teamwork are better positioned to anticipate the needs and actions of other members, thereby increasing team performance” p. 877. Hence, studies of team or shared cognition commonly involve indirectly or directly capturing team member’s individual models and the team’s shared mental models. Researchers in shared or team cognition, then, use *paired comparison ratings, concept mapping,* or *card sorting* to directly illuminate the subjects’ mental models, or researchers use other *qualitative methods* such as coding documents or videoed team interactions in order to deduce the subjects’ individual and shared mental models (see Mohammed et al., 2010. for review, including summary tables that include research setting, methodologies, goals, and representative authors).[40] These discovered or described mental models are then used to explain team performance outcomes (e.g., safety, efficiency, communication, decision-making quality) and, potentially, to prescribe more effective team training protocols.

Research on shared or team cognition occurs mostly commonly in situations where a team must perform some task that cannot be accomplished by an individual. Such situations include military training simulations, negotiations, managerial decision-making, and air traffic control (see Tables 3 and 4 in Mohammed et al., 2010). Such tasks are often complex and technical, and require extensive and precise coordination among

[40] Mohammed (2010) and Cannon-Bowers (2001) provide excellent introductions to the field.

people, but the tasks are not generally scientific exercises or focused on creating a design. They are more operational and involve situations in which decision points occur rapidly and decision consequences can be severe. The overarching goals of shared cognition research are to improve team performance through a better understanding of team cognition and to develop and implement more effective training for team members in those particular situations. Of course, by developing shared cognition theory, researchers attempt to generalize beyond particular situations.

Shared cognition research deals with situations outside the realm of engineering design. In team design, decisions can be unmade, and their consequences can be mitigated through reflection. More important is that team design involves shared focus on the creation of shared common objects, i.e., the design itself. This feature, central to research on design thinking and practice, is absent from the research in shared or team cognition. Shared cognition theory could apply to design situations, as Pea (1993) points out; however, the cross-over between the two bodies of work is small. Taking a cross-walk between research on shared cognition and research on team design is worthwhile, but since this dissertation already draws on work from at least four more or less distinct bodies of research (e.g., classroom argumentation, Pragma-dialectic theory, design thinking and practice, and cognitive psychology), the possible incorporation of shared cognition research is left to future work.[41]

DESELECTION OF DESIGN CONCEPTS

Research on designers working together in situ is often focused on attaining a better understanding of design process and design thinking (cf. *Design Studies*, 2011, 32(6)). With that goal in mind, researchers will often use protocol analysis and attempt to uncover properties of design processes and thinking by using the designers' discourse as

[41] Also, while reviewing this literature, I found myself witness to an imbroglio between two philosophical camps: the socio-cultural view of cognition (cf. Cole and Engestrom, 1993), and the cognitive view (cf. Salomon, 1993). Essentially, researchers have been trying to answer the question, "Where does cognition exist—inside or outside the human brain (mind)?" The answer, in my opinion, is "both," and given that we cannot place ourselves in a third realm—neither inside nor outside the brain—we will never know for sure. It is an academic delineation to suppose that there exists some boundary between the mind and the environment. Beginning with that supposition, researchers can take one perspective or the other to formulate questions, devise methodology, and conduct studies that help us to understand the nature of human thought. The assumption that a cognitive boundary exists has helped produce tremendous insight into the nature of human thought. However, I wished to avoid that debate in the content of my dissertation.

an entry point. Since I was focused primarily on my students' discourse, rather than on their design process, and since I used their designs mostly as a point of reference to understand that discourse, I avoided some of the ideas and terms commonly found in research on design.

Design researchers speak of problem space, solution space, problem scoping and solution generation (Adams, Turns, & Atman, 2003; Coley, Houseman, & Roy, 2007; Dym, 2005). I did not use those terms to delineate what stages of the design process the students might or might not have been in. I did make the distinction (see Chapter 4) between student discourse that looked like argumentation but was not productive and student discourse that seemed to mark collaborative and effective efforts. However, my distinction of their discourse could exist within both the problem space and the solution space. Again, I was not focused on design process, except in a general sense, so using these terms would not have been illuminating, at least not in this exploratory study.

Design researchers also speak of 'framing' (Cross, 2004; Lawson & Dorst, 2009; Dorst, 2011) and how it relates to design thinking and even argumentation in a design context (Stumpf & McDonnell, 2002). Bjorklund (2013) defines framing thus:

> Framing refers to the creation of a standpoint from which a problem can be successfully tackled (Dorst, 2011), and requires a process of structuring and formulating the problem (Cross, 2004). Whereas design problems can have some inherent structure, for example in terms of the number of main issues or amount of dependencies between issues (Dorst, 1996), problem structuring refers to the psychological process of forming a mental, subjective representation reflecting the perceived problem state and desired outcome (Simon, 1973). p. 136

Framing originated with Schon (1983), and it is a mental and psychological phenomenon that exists in the minds of designers. Researchers approach framing though mental problem representations (Bjorklund, 2013;) and designer discourse (Stumpf and McDonnell, 2002). Framing is also considered when regarding how designers apprehend a design problem (Schon, 1988). The goal of my research is to characterize the students' argumentation structures, and not to characterize their mental models or design framing.

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